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THE EASTERN KENTUCKY GAS FIELD

A geological study of the relationships of Ohio Shale gas occurrences to structure, stratigraphy, lithology, and inorganic geochemical parameters

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FINAL REPORT

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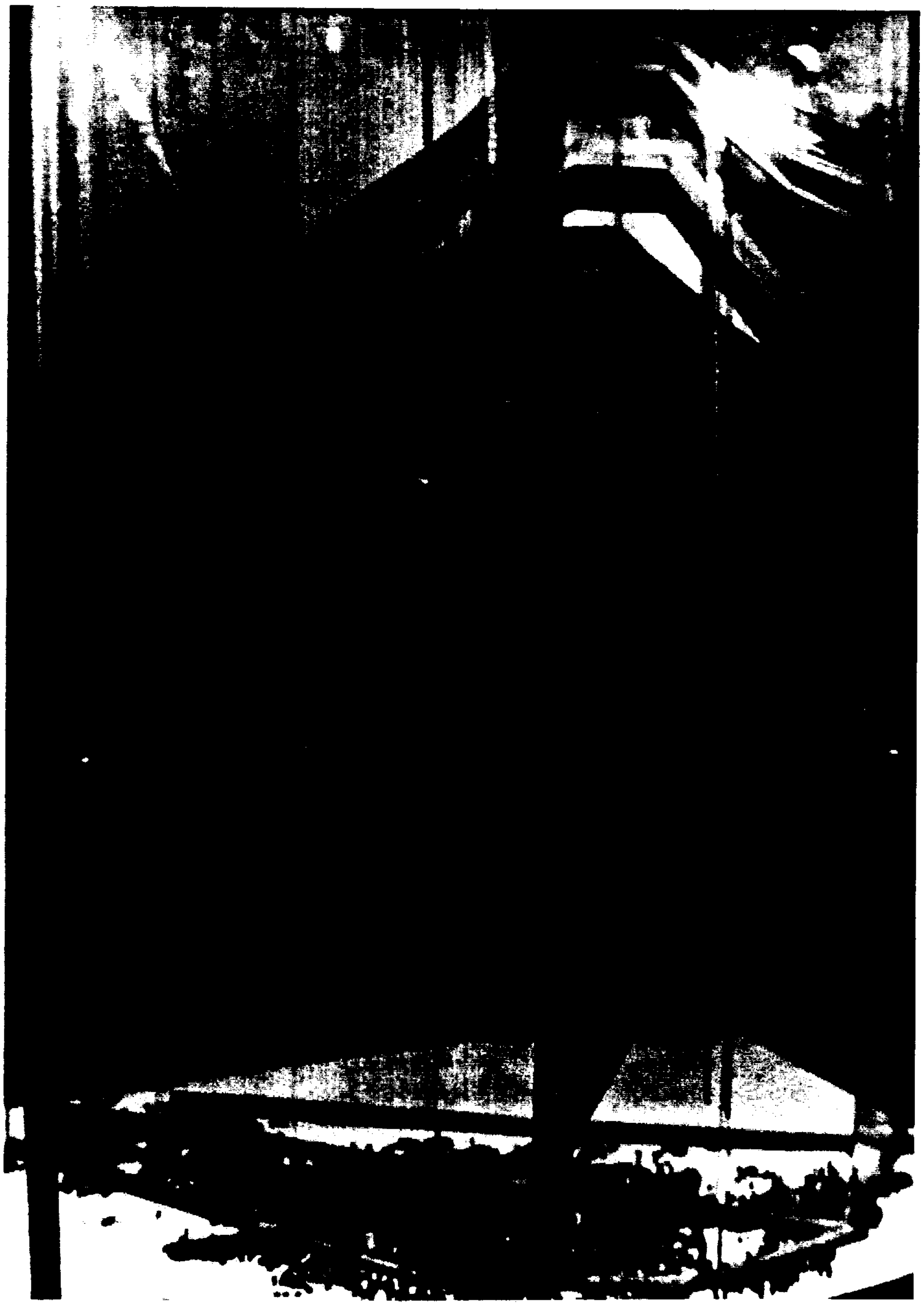

Frontispiece: 3-D plexiglas model of structural-stratigraphic cross sections and nail histogram of open flow data. North is to the right border of the model base.

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To Mrs. Mary Queen, secretary of the Department of Geology and Geography, goes especially warm appreciation for operational assistance.

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ABSTRACT

The largest gas field in the Appalachian basin is examined in terms of: 1) structural elements described in existing literature, 2) stratigraphic relationships derived from gamma-ray logs, 3) lithologic sequences from well cutting studies, and 4) inorganic geochemistry of elements and minerals from well cuttings. Final open flow data from approximately 4750 wells producing from the Upper Devonian black shale are compared with the geological parameters.

The Eastern Kentucky Gas Field, a coalescence of many fields, is concluded to represent a highly complex structural-stratigraphic gas trap. Stratigraphic relationships dominate the origin and occurrence of the gas in the black shale facies, but structural constraints on basinal configuration and subsequent doming and uplift in the southeast probably resulted in gravity tectonics, decollement features, and compressional stresses, contributing to a widespread fracture facies concentrated in the Huron member of the Ohio Shale.

This fracture facies may be enhanced by the occurrence of complex intertonguing of organic black shale with silty gray shale in the center of the area of high gas production.

Radiating and circular fracture zones (interpreted from open flow patterns), related to the Paint Creek Uplift, probably provided conduits for the major pattern of gas

accumulation off the nose of the uplift. High pressure zones in the shales are probably a result of the compressional and compaction relationships, coupled with the fracture conduits over the nose of the Paint Creek Uplift.

The mineralic ratios, determined by geochemical analysis, suggest an upper Devonian environment dominated by relatively fresh water, marginal, cratonic swamps, which were periodically destroyed, the organic debris from which contributed to the black shales accumulating at the toe of the prograding eastern deltas.

Inorganic elemental geochemistry shows promise as an exploration tool. The contoured data on the oxides of Si, Al, Mg, K, Fe, Ca, the ratio Si/Al, and S result in maps which show configurations similar to the density of high producing wells.

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I. INTRODUCTION

A. Purpose

The purpose of the study presented here is to relate gas occurrence and production potential (as interpreted from open flow data) in the Upper Devonian black shales in eastern Kentucky to geological parameters, including regional structure, fracture frequency, stratigraphy, lithology, and inorganic geochemistry. Understanding of these relationships may provide better models for black shale gas production, a practical framework for field expansion, and may suggest constraints for technological advances in recovery methods.

The Big Sandy, as the original field is called, and the surrounding areas in eastern Kentucky account for about 90% of the total gas production in Kentucky; about 75% of this is produced from Devonian black shale; and about 92.2% of the black shale gas is produced from secondary reservoirs with vertical joints and fractures according to Hunter (1964). The source beds are the organic black shales and the primary reservoirs are the silter or sand layers. Coleman D. Hunter worked on this problem for nearly thirty years as chief geologist for Kentucky-West Virginia Gas.

B. Scope and Data Bases

Structural information and maps are primarily derived from existing, published and unpublished literature.

Stratigraphic relationships and structural-stratigraphic cross sections are based on gamma-ray logs selected from 300 well logs supplied by Kentucky-West Virginia Gas Company.

Lithology studies are conducted on about 600 samples of well cuttings from thirteen wells. All cuttings are from cable tool-drilled wells with one exception near the Pine Mountain Thrust. These samples are supplied by Kentucky-West Virginia Gas Company.

Inorganic geochemical analyses (x-ray fluorescence and x-ray diffraction) were performed on all samples used in the lithclogy study, plus an additional well, totalling aproximately 700 samples.

Final open flow data from approximately 4750 wells are abstracted from Kentucky-West Virginia Gas Company maps.

C. Background

The Eastern Kentucky Gas Field may be considered a coalescence of many fields covering an area of about 3000 square miles and centering over a field better known as the Big Sandy (Figure 1). See Figure 1 for location of study area. This area has produced gas from the Upper Devonian black shales for nearly one hundred years; some wells are still economically productive after more than fifty years. The stratigraphic sequence of major interest in this study is the Ohio Shale, including the Cleveland, Three Lick, upper Huron, middle Huron, and lower Huron units. The Berea/Bedford sequence has been included where data permitted. See Table 1 for Stratigraphic relationship of Ohio Shale with the New Albany Shale and Chattanooga Shale, and Table 2 for stratigraphic units studied, with general gamma-ray log characteristics (Provc, 1977) and lithology. Figure 1 shows the formational terminology (after Swager, 1978).

The enigma of gas production from a tight shale with both low porosity and low permeability has plagued geologists in the area since the field's inception (Hunter, 1935). Although some relationship was found with anticlinal structures, gas was also recovered from synclinal areas and troughs. As the field area developed, intricate and possibly inter-connected fracture geometry was suggested by the gas recovery pattern (Figures 2 and 3, after Hunter and Young, 1953).

As well cuttings were examined it became apparent that a relationship also existed between gas recovery and the occurrence of thin silty or sandy layers in the black shale. These siltier layers were related by several early workers to shore-line facies on the epicontinental shelf, as well as stringers related to deltaic progradation (Hunter, 1953; Thomas, 1951;

Billingsley, 1934; Lafferty, 1935; and McFarlan, 1943).

With increased demand, accompanied by increased prices for fossil fuels, interest in more intensive and efficient recovery of gas from black shales spurred research on potential gas recovery from the Upper Devonian black shales in the Appalachian basin. This study is a part of the research funded by the Department of Energy in the Eastern Gas Shales Project, and represents an effort to bring together as much known data about the area as possible in combination with additional research on lithology, geochemistry, and analysis of open flow data.

This study presents the general field relationships and focuses the need for detailed studies in areas such as 1) fine structural features related to the Ohio Shale production in eastern Kentucky, 2) the role of lithological variation in gas production, and 3) the need to develope a technique to study fracture frequency and relationship of fractures to siltier layers. (See Suggested Future Problems for Study).

II. DATA USED IN THIS STUDY

A. Summary of Previous Structure Maps

Various structural horizons have been studied in the field area at widely separated times. The maps existing in the previous literature are reviewed as a framework for the present study.

1. Accordant Summit Level

A study of accordant summit levels by McFarlan and Haag (1940) shows an area physiographically "not beyond early maturity, so that early upland levels are still represented in the accordant hilltops." (Figure 4, after McFarlan, 1943). There is a major east-west trend to the strike of the contours in the center of the field.

2. Structure on Top of the Fire Clay Coal (Pennsylvanian)

Structure on top of the Fire Clay coal is shown in Figure 5. A closed southern basin is observed on the 1000-foot contour. The shaded 900-1000-foot elevation interval shows an interference figure on the structural surface, with two crossing directions: northeast-southwest and north-south. The junction of these trends at this structural level is the point at which the north-south trending Paint Creek Uplift intersects the eastern Kentucky syncline.

Relationsips of the Fire Clay coal attitude at present and at time of deposition are contrasted with the attitudes of the older shale under the section on Anaysis of Data.

3. Coal Face Cleats

Coal face cleats measured by Long (1979) show a radiating pattern about a southeastern focus. See Figure 6. This pattern compared with Figure 5 shows a parallel relationship of face cleat directions to dip of structural contours on the Fire Clay coal. Long has suggested a directional constraint on the coal face cleats imposed by depositional basin configuration. It would appear that the face cleats may also be related to the uplift structure in the southeast, imposed on the coal after deposition. If coal cleats are related to this uplift and compression, the shale fractures or more intense fracture zones (described under 4. Density of High Open Flow Wells, page 32, and Figure 79) may also be related.

4. Structure on Top of the Berea

Structure on top of the Berea sandstone is shown in Figure 7 (after Thomas, 1951). Faults of the eastern Kentucky system are seen trending east-west across the upper left quadrant of the map. The Paint Creek Uplift dominates the structural configuration with a north-south trend entering the field from the north and changing to a broader southeastern slope.

5. Structure on Top of the Ohio Shale and Subcrop Structure (Hunton age)

Structure on the top of the Ohio Shale (Provo, 1977) is shown in Figure 8. Provo used about 250 data points, including drillers' logs and gamma-ray logs in the compilation of this map. Data points in the central area were sparse. Unfortunately, available gamma-ray logs for the present study also were lacking in the Floyd County area which is the center of highest production. However, some irregularities in contours suggesting smaller structure in Floyd County are apparent in Figure 8.

The 0-foot and 500-foot isopach lines for the Hunton age strata underlying the Ohio Shale are shown in Figure 1. (Weaver, 1973). The erosional surface on the Hunton sloped to the east, northeast.

6. Evidence of Rome Trough Growth

The Rome trough, a basement structure buried under Middle and Upper Paleozoic sediments, probably originated in Late Precambrian time; however, major development of the asymetrical graben occurred in Lower to Middle Cambrian time. Evidence for this dating is observed in the thickened sequences of siltstones, shale, and sand comprising the Rome formation (See Figure 9, after Dever, et al., 1977).

Associated with the Woodward Fault Zone, which trends northeastward and borders the study area on the north, (Figure 10, after Silberman, 1972) Cambro-Ordovician growth faults have been described trending east-west. Near the junction of two of these faults with the Woodward Fault Zone, a Permian igneous intrusive and surface dikes are described by Silberman (1972). The relationship to the northwestern corner of the study area is shown in the inset map.

7. Basement Structure

Basement structure has been interpreted by Ammerman and Keller (1979) from the Bouguer gravity map (Figure 11). The Floyd County Channel, extending northward into the center of the field, is suggested by these authors to be an aborted rift, entering the Rome Trough at the same structural elevation as the trough at that point. The Pike County Uplift and Perry County Uplift are shown well within the study area. The interpretation by Shumaker (1977) shown in Figure 12 (Negus-deWys and Renton, 1979) suggests that the Floyd County Channel is a saddle with the two flanking uplifts farther apart. The Rome Trough is shown as a complex graben with wedge-shaped blocks successively more down-thrown to the northeast. The trend of the trough changes rather abruptly to a more northerly direction after it enters West Virginia (Negus-de Wys and Renton, 1979).

8. Relationship of the Study Area to Precambrian Geological Provinces and Orogenic Trends

Figure 13 (after Muehlberger, et al., 1967) shows the study area to be located at the boundary between two provinces, the 1.35 billion year-old cratonic mass with north-east orogenic trend lines and the younger

1.0 billion year-old province with north-northeasterly orogenic trends. The Paleozoic, paleogeographic epicontinental shelf is suggested by Paul Price (Lafferty, 1941) to run directly through the center of the study area, covering most of the map area, with a slight easterly bulge in the center of the field (See Figure 14). The New York-Alabama lineament, based on aeromagnetic data (King and Zietz, 1978), trends northeast-southwest to the southeast of the field. This lineament has been interpreted by King and Zietz as a possible Precambrian plate suture.

9. Sequential Structural Development in the Study Area

The sequential development of the structural setting of the study area is shown in Figure 15 (Negus-deWys, 1979), and suggests an active basement involvement from Precambrian to Recent time. Detachment and gravity tectonics in late Paleozoic time will be discussed under Data Analysis. The Precambrian New York-Alabama lineament is not shown (See Figure 14). Structures shown include: 1) Precambrian: Rome Trough, Floyd County Channel; 2) Cambro-Ordovician: major Rome Trough development, growth faults, and Waverly Arch trend; 3) Silurian-Devonian: Cincinnati Arch, initiation of the eastern Kentucky syncline; 4) Mississippian: Paint Creek Uplift, Waverly Arch (west), and the Pike County and Perry County uplifts; 5) Pennsylvanian: Pine Mountain Thrust movement initiated and major development of eastern Kentucky syncline; 6) Permian: intrusive igneous body and surface dikes associated with east-west growth faults intersecting the Woodward Fault Zone. Growth of selected basin faults in the Rome Trough area continues to Recent time.

B. Stratigraphy from Gamma-Ray Logs

Stratigraphic units in the Ohio Shale, when interpreted from gamma-ray logs, are related to differing log signatures. These may or may not be identical with the outcrop lithologic units. The Three Lick bed which shows a unique log signature across the field area has also been found to be easily traced in outcrop. Other units are not always easily distinguished in outcrop. It was possible to obtain good samples from only one well which included a gamma-ray log. However, a nearby well which had a gamma-ray log was selected to study with samples in order to assess correlation problems.

1. Devonian Shale Stratigraphy

Emphasis in this study is on the Cleveland, Three Lick, and the Upper, Middle, and lower Huron units of the Ohio Shale. The Berea/Bedford sandstone and shale is included where data permitted (See Table 1). A comparison of nomenclature used for the Ohio Shale, the Chattanooga Shale, and the New Albany Shale is shown in Table 2. For areal delineation of nomenclature, see Figure 1.

Provo (1977) and Swager (1978) provide extensive reviews of the stratigraphic descriptions in the literature. Assistance in identification of unit tops was given by Ed Wilson and Z. Zagar of the Kentucky Geological survey; W. deWitt, Jr., of the U. S. G. S. ; Doug Patchen of the West Virginia Geological and Economic Survey; and R. Hagar and E. Jenkins of Kentucky-West Virginia Gas.

2. Cross Sections

The locations of cross sections constructed from gamma-ray logs are shown in Figure 17. See Figures 18, 19, and 20 for the stratigraphic cross sections. The trace characteristics of each unit are apparent. High natural radioactivity is observed in the Cleveland which is a highly organic black shale in the northern and western portions of the field. The gray shading represents the highly organic black facies. The unshaded Cleveland is a silty gray shale which appears to intertongue from the east and southeast. It has a lower natural radioactivity, and less apparent organic material. The gray facies of the Cleveland appears from the logs to resemble more closely the typical gray Chagrin Shale (of the Ohio Shale in Ohio) to the northeast of the study area. The Cleveland thickens by a factor of 5 to 6 from southwest to northeast.

The Three Lick Bed characteristically shows three zones of low radioactivity that suggest three cycles of deposition. In outcrop the Three Lick appears as green silty or mud-shale layers interbedded with dark organic layers. To the east in the Big Sandy Field this unit thickens slightly and shows a more complex radioactivity pattern suggestive of additional silty layers. This unit also becomes less distinctive in its radioactivity signature as it is traced on logs eastward to the edge of the field area and would suggest additional silty layers.

The upper, middle, and lower Huron units form a cyclic assemblage. The lower Huron shows the highest radioactivity, with the upper Huron second, and the middle Huron showing the lowest radioactivity. The lower Huron also shows the greatest log complexity, suggesting black organic layers thinly interbedded with silty layers. If the assumption is made that natural radioactivity may be equated with organic content, the middle Huron log signature suggests that the dominant lithology is a silty shale with less organic material. Evidence for the lack of correlation of natural radioactivity with gas content of the shales has been shown by Kalyoncu, et al. (1979). Thus, in these cross sections, it should be noted that stratigraphic units being correlated are radioactivity signatures and not necessarily continuous lithologies, lithofacies equivalents, or strict time unit equivalents.

In Figures 21 and 22, cross sections are shown with the top of the Berea as the datum. Gas occurrence information was generated where temperature logs were available; however, temperature log data was not available for all wells. In wells where no gas is indicated, the ommission may be because of the lack of data. Gas may occur at any level in the sequence and the general practice is to "shoot" the entire section in completion procedures. In Perry County temperature logs are noted by Ray (1968) to confirm that most of the gas was coming from two zones: the upper Berea/Bedford and the lower "Hot Shale" unit in the upper Devonian (lower Huron). Figure 21 shows the interpreted intricate intertonguing of black and gray shales to be especially well developed in the heart of high production in Floyd County. Figure 22 shows the simpler gamma-ray log signature and relatively thin occurrence of the Cleveland at the southwestern edge of the field.

In all cross sections the relatively uniform thickness of the Berea/Bedford may be noted. However, the signature changes across the field from a characteristic sand signature in the northeast to that of shale in the southwest.

The next seven Figures, 23-29 inclusive, are structural-stratigraphic cross sections with a 1:163 ratio of horizontal to vertical scale exaggeration. The steepest dip is approximately 50 feet to the mile. The open star symbols represent gas occurrence; the solid star symbols represent known oil occurrence.

Again, lack of data may account for wells without hydrocarbons noted. The gas occurs throughout the sequence, on structural highs, lows, and flanks of the Paint Creek Uplift which dominates the structural configuration of the field. Figures 23 and 24 may extend into the Rome Trough; Figure 24 shows evidence of faults at the southwestern end of the section. See Frontispiece for 3-D model of structural-stratigraphic sections.

3. Isopach Maps

Figure 16 shows the isopach map of the Berea/Bedford sandstone (after Pepper, Demarest, Merrels, 2nd., and deWitt, Jr., 1946). The unit becomes almost one hundred percent shale in the west and southwest, and from gamma-ray logs appears to be very uniform in thickness over the field. It is the lithology which changes and is perhaps what is reflected in Figure 16. Also see Figure 50.

Figure 30 shows isopach maps of the Cleveland, Three Lick, upper Huron, middle Huron, and lower Huron from Provo (1977). About 250 data points from drillers' logs and gamma-ray logs are utilized by Provo in the study area shown in these maps. No great improvement in coverage could be gained by the addition of logs available for this study. (See location of available logs under lithology studies.)

Figure 31 shows the isopach map of the total Ohio Shale sequence. The strike of isopachous lines changes with time; the total section shows a basic N-S trend in the strike of the isopach lines. All units thicken to the east, but with varying rates, with the exception of the Three Lick, which actually shows an isopach closure. These rate changes across the field will be further discussed under lithology studies in relation to bentonite occurrence.

4. The Berea/Bedford-Cleveland Boundary Problem

As consultations were held with various specialists in the field, concerning the best "pick" for the top of the Cleveland, it became abundantly clear that there is not total agreement on this subject, especially in areas where the Berea/Bedford loses its silty or sandy character and becomes shale, or in cases where the Cleveland shows a siltier nature. Such "top" problems are probably best decided on the basis of lithology and radioactivity studies, and where possible, with the addition of biostratigraphy.

Gamma-ray tops used in this study are in agreement with the Kentucky Survey (Wilson, 1979), U.S.G.S. (de Witt, Jr., 1978), and Kentucky-West Virginia Gas (Hager and Jenkins, 1977-79).

5. Fine Structure in Log Response of the Huron and Cleveland Units

Changes in the log signature of the Cleveland suggests complex intertonguing of black organic shales from the north and west with silty gray shales from the east and southeast. This reflects the delta toe sedimentation interrupted or interspersed with organic black muds, probably largely derived from the craton.

A similar, and in some cases more erratic, fine intertonguing is observed in log signature comparisons in the lower Huron. High radioactive zones are sometimes higher than in the Cleveland, but these spikes are not as easily correlated across the field. However, an illuminating study would be one in which the fine gamma-ray response for the lower Huron is studied and related to the other parameters, including lithology.

C. Lithology Studies from Well Cuttings

1. Well Locations

Cuttings from very few wells were available for study. Frequently in the center of the field cuttings are blown out of the wells when high pressure zones are encountered.

Figure 32 shows the locations of wells from which cuttings are studied. All samples were from cable tool-drilled wells except well #7289 which was drilled by rotary. Small dots are locations for wells from which gamma-ray logs are available. Not all, however, are useable for this study.

Samples representing drillers' runs varied from two and one-half-foot intervals to as much as 30-foot intervals. The majority of samples are from 10-foot intervals. Fourteen wells and a total of about 600 samples were examined wet using a binocular microscope with reflected light under 10X and 30X magnification.

2. Cross Sections

The mudrock terminology Of Folk (1974) is used. See Table 3. Table 4 shows lithology symbols for cross sections. Early in the study it became apparent that the Ohio Shale sequence is predominantly very silty silt-shale in some wells, although this sequence is usually referred to as "brown shales."

In constructing cross sections it is deemed advisable to use the base of the Huron as the datum line because it is easily recognized and because of difficulties in correlation higher in the stratigraphic sequence.

Cross sections A-A', B-B', C-C', and D-D' are shown in Figures 33, 34, 35, and 36. Section A-A' (Figure 33), from southwest to northeast, shows the thickening section to the east. The Berea is 100% shale in the southwest grading into a siltstone with some sand grains in the east and northeast. Some dolomitic cementation is observed in the siltstone. In the Eastern Kentucky Field the Berea is of nearly uniform thickness over the entire area, but does show changing lithology.

The Cleveland Formation is a black to dark brown, at times greasy looking, highly organic siltstone in the southwest. It grades into a browner silt-shale and then to brown mud-shale in the east, where it intertongues increasingly with gray clay-shale and mud-shale.

The Three Lick is designated as the "upper banded shale" by Swager (1978) at the outcrop. This banding of green and gray and brown shale is also apparent in the well cuttings. In some wells, silty zones are apparent.

The upper Huron is usually a brown, highly organic mud-shale, and is the "lower black shale unit" of Swager. The middle Huron is less organic, siltier, and frequently shows interbedding of gray or green with black shale. The lower Huron is very highly organic, black to dark mud-shale and may show some interbedding. It breaks into blocky rather than plate-like fragments. In the outcrop it also appears blockier and less fisssle than the Cleveland or other Huron units.

For comparison with the lithological cross sections, similar sections using logs may be compared (Figures 18, 19, and 20) as well as the structural-stratigraphic sections (Figures 23-39 inclusive). These are not identical lines of section, because logs are not available for most of the wells from which well cuttings are used. Only one well from which cuttings were studied, could also be studied by gamma-ray log. Gamma-ray logs are only available for wells #7289 and #6869, neither of which could be considered key lithologic logs.

In cross section A-A' the center well appears to be lacking part of the lower Huron and shows a milky white chert and limestone unit. This is probably Huntersville Chert (Hager, 1978). The chert continues for approximately 75 feet with a tan-gray sandy, fossiliferous limestone and dark brown sucrosic dolomite. Stylolites occur in the limestone. This well, located more centrally in the field, shows indications of fractures at 29 different horizons. The lowest part of the Huron, which is usually black shale, is not present in the well and could be a normal fault with 75-100 feet displacement in the Huron, eliminating the lowest part of the Huron and bringing the Huntersville Chert in higher in the section. Such a fault on the side of the Floyd County Channel would not be unreasonable. Other possibilities are 1) the collection of samples and 2) detachment tectonics related to the southeastern uplift. See section on Data Analysis.

The Boyle cherty limestone, observed to occur in some outcrops below the New Albany Shale, appears similar to the cherty well cuttings. The relationship of the Boyle and Huntersville is presently under study by Conklin (Wilson, 1979).

Cross section B-B' (Figure 34), north-south through the center of the field, shows the thickening of the section to the south. Redbeds occur in the northern two wells, but not in the southern where the sections show more silt. The most southeastern well appears to show repetition and, thus, may represent a faulted section. However, the increased slickensides which would be expected to accompany such an interpretation, are not apparent in the well cuttings.

Protosalvinia ravenna (a bifurcated form of the brown alga) occurs near the top (Cleveland Formation) of the Southern-most Knott County well (Protosalvinia is not found such an horizon in other wells) and section repetition appears in the Knott County well, suggesting thrust faulting. A gamma-ray log from a well within 2 miles to the north does not show signature abnormalities, and thus, does not substantiate such an interpretation at that distance in that direction. Protosalvinia occurrence has usually been reported as restricted to the middle Huron just below the center of that unit. Provo (1977) and Swager (1978) do report occurrences from the Three Lick down through the lower Huron. Occurrence of forms suggestive of such a stratigraphic range are also found in these cuttings; publication of such results will await further study.

Tasmanites has been determined by Jux (1971) to be the spore of a green alga. This spore is very common throughout the sequence, both as a carbonaceous form as well as pyritized spheres. It would appear that the shales were a veritable algal soup!

Archaeopteris is a characteristic Upper Devonian plant represented by 15 or more species and recorded from numerous localities in New York, Pennsylvania, and eastern Canada, from Great Britain, Ireland, Belgium, Germany, and U.S.S.R. and from high latitudes in Ellsmere Island and Bear Island (Andrews, 1961). Lee and Tsai (1978) also report occurence in China. Beck (1960) announced the important discovery of finding a pyritized stem with *Callixylon* wood structure bearing several fragments of *Archaeopteris* fronds. Thus, they are one and the same plant. Specimens of *Callixylon* exceeding five feet in diameter are reported in the Upper Devonian of Oklahoma. It is thus the largest known Devonian plant. Petrified wood of *Callixylon* is found in the Ohio Shale outcrop in Kentucky in several localities and is described by McFarlan (1943) in discussion of the Huron Member. This suggests swamp development with sizeable tree ferns existed not far from the study area. Such swamp development could contribute the black muds from the craton area during periods of higher rainfall. See Figure 37 for a drawing of Archaeopteris. Woody, vitrinite fragments are common in the gray shales. The source plants were not identified.

Moore (1929) and Twenhofel (1939) postulated near-shore, shallow water environment and, in the absence of evidences of wave action, according to Rich (1951), are forced to postulate choking of the water by aquatic vegetation to such an extent as to damp out wave action. Because the Callixylon logs had not yet been associated with the Archeopteris fern-like fronds, and were thought, from the woody tissue, to be conifer-like, Rich (1951) argued that if the masses of vegetation were dense enough to damp out all wave action, it would seem that they would also have prevented the floating-in of the great logs of Callixylon which are so common in certain parts of the shales. Pelagic organisms such as cephalopods and pteropods are further offered by Rich as evidence of deeper water. However, the model of marginal swamps periodically inundated by marine fluctuations could satisfactorily explain the data. See Figure 37b for depositional model, after Twenhofel (1939).

To quote from Moore (1929) in discussing probable conditions of formation of Pennsylvanian age black shales

: "perhaps the only difference between these and some of the so-called normal types may be restricted circulation due to abundant plant matter, or the presence of a large quantity of humous materials derived from drowned coal swamps."

3. Lithofacies Maps

Recognizing the scarcity of data points, which was caused by lack of available well cuttings, data were contoured. The resulting lithofacies maps are presented with full awareness of the restricted data, but with a suggestion that the results are meaningful when compared with the other data.

In examining the well cuttings the rock types are noted and described, occurrence of plant and animal fragments are noted, as well as indications of fractures. Fracture indicators which were used include: slickensides, open fractures, filled fractures, fracture sides with attached spar, and separate spar crystals. Stylolites occur in the limestone unit in the bottom of the central well (Section B-B') with the Huntersville Chert.

Frequency of fractures was contoured (Figure 38). Because of the differences in sample intervals and the inherent problems in the fracture indicators (caving, slickensides from drilling, etc.) the author was extremely dubious about this aspect at the onset of the study. However, the resulting configuration appears reasonable, and did not require much alteration of contour lines when fractures from cored wells were added (Evans, 1979). Wells were examined in no logical sequence and not compared until all were completed. Nonetheless, a more objective and replicable method of obtaining fracture frequency data would be desireable.

Maps of relative percentages of gray, brown, and green shale in the total Ohio Shale sequence studied (Cleveland-Huron) are shown in Figures 39, 40, and 41. The isopach map of black shale is shown in Figure 42.

The configuration of the Devonian black shale isopach shown by Harris, de Witt, Jr., and Colton (1978) (Figure 43) should be compared with the combination of the brown shale and black shale of this study (Figure 40 and 42). In the compilation of the map by Harris, et al., de Witt included organic black and brown shales together (Figure 43), whereas the maps in this study separate the two.

Percent shale of total Ohio Shale sequence is shown in Figure 44 which may be compared to percent of silt and sand in Figure 45. Higher silt/sand areas occur in the northeastern section of the field and a patch southwest of field center. If the silt/sand percentage is contrasted, Figure 46 results, showing finer grained clastics to the southwest and coarser material to the northeast. Percent carbonate is shown in Figure 47. It shows a marked similarity to the isopach map of the "Corniferous" (McFarlan, 1943) seen in Figure 48. "Corniferous" includes limestones of Maysville (Upper Ordovician) to Hamilton (Devonian) formations. Hamilton underlies New Albany (Ohio Shale equivalent). Thus, the suggestion from the "Corniferous" isopach map that a northeastern basin in the Rome Trough complex was in existence during "Corniferous" deposition, leads to the conclusion that this northeastern basin, later known as part of the eastern Kentucky syncline, may have been defined as a deeper segment as early as Upper Ordovician (Maysville). Comparing sediment thicknesses suggests that in early Pennsylvanian time this northern basin was particularly well developed (McFarlan, 1943).

Percent redbeds of total sequence is shown in Figure 49. An area trending northeast-southwest across the study area shows occurrence of redbeds with the highest values to the northeast. This suggests a positive area during late Upper Devonian time, or preferential currents depositing detrital fragments from eastern deltaic origin.

The results of very scanty data on the Berea-Bedford show the unit to be 100% shale in the southwest, and, if the trend is extrapolated, the 50:50 shale:sandstone ratio line would run through the heart of the gas field. The isopach map of the Berea-Bedford (Pepper, et al., 1946) shows the sand in a highly complicated patchy thinning and thickening in the Floyd County area (Figure 16). (See Figure 50 for cross section.) From the gamma-ray logs the Berea-Bedford appears to be of nearly uniform thickness over the field. Thus, the lateral changes in lithology in the cross section may be regarded as facies changes. Other possibilities are erosional genesis and local structural anomalies. The small scale thins shown in the isopach map in the central area of the field may relate to growing structures.

Detailed structure maps on the Big Lime (Mississippian) in this area (Figure 51, after Miller and Withers, 1928, referenced in McFarlan, 1943) show several fine structures superimposed on the northwest regional dip.

4. Correlation of Gamma-Ray Logs with Sample Study

It would have been ideal to use samples from logged wells, but of the sampled wells only one gamma-ray log was useable of the two obtained. Nearby logs were used when available.

In the areas surrounding the center of the Eastern Kentucky Field area, the lithologic units as described from samples are easier to identify with gamma-ray logs of nearby wells. However, in the central part of the field, most of the production occurs in the area of maximum lithologic complexity. This probably is not fortuitous. The correlation of lithology to natural radioacitivity in this area appears extremely difficult and questionable. The natural radioactivity need not relate directly to high organic content, so this lack of correlation is not surprising. Scale restrictions and the few number of wells studied dictate that the lithologic complexities be greatly simplified in the figures, but the isopach maps suggest complex depositional intertonguing of cratonic-derived, organic black muds with distal deltaic silts and clays. (Black organic muds also appear in the lower Huron from the east.)

D. Inorganic Geochemistry Studies from X-ray Fluorescence and X-ray Diffraction of Well Cuttings

The same cuttings included in lithology studies were utilized in geochemical analyses, with the addition of one well, #1660. From 1935 to 1964 Coleman Hunter studied the Eastern Kentucky Field and from well cutting examinations he published average values for quartz, pyrite, kerogen, and bituminous material (Hunter, 1964). Maps showing iso-value lines based on these data are shown in Figures 52, 53, 54, and 55. From the same study Hunter's estimated ultimate recovery per well is shown by county in Figure 56. The quartz map shows high values to the east; pyrite is high in Floyd County and may extend north; kerogen is high in Floyd County and on to the northwest; bituminous material is higher to the northwest and low to the east-southeast; and the estimated recovery contours show an elongate oval configuration with a northeast-southwest axis.

1. Elements Analyzed

Elements analyzed include Mg, Al, Si, P, K, Ca, Ti, Mn, Fe, S, Cu, Zn, Sr, and Na. All elements except sulfur are analyzed as oxides. The ratio of the oxides Si/Al is also studied.

Table 5 shows the elements analyzed with minimum, maximum, and mean values, variance, and coefficient of variance. Variance is the average of the square of the deviations of the measurements about their mean;

coefficient of variance is the standard deviation (variance) divided by its related mean, and is a relative measurement of deviation.

A comparison of Si and Al oxide graphs for the Berea/Bedford through Huron sequence is shown in Figure 57. The wells are arranged from west to east. Figure 58 shows the Si oxide graphs in the well positions. Field cross sections of the Si-Al oxide ratios are shown in Figures 59, 60, 61, and 62 with stratigraphic units noted. Legend preceeds figures.

Figure 58 shows great similarity among wells in the northeastern portion of the field (#5584, #5963, and #5903), some similarity in the southwest (#1678, #1380, #7272, and #7289), and practically none in the center (#965, #1486, and #5909). In the cross sections the 4 = a ratio of 4:1 in the Si/Al oxide ratio. Again, the center of the field shows more diverse relationships.

2. Computer-drawn Maps of Elemental Data

From these data, computer maps are run on the average values of individual stratigraphic units, for the total sequence, and for the Ohio Shale. The map for the Si oxide in the Three Lick unit is shown in Figure 63.

A comparison of computer-drawn map miniatures is shown in Figure 64 for all units for Si/Al, Al, Si, S, Mg, K, Fe, and Ca. The darkest shade is the highest value, the lightest shade represents the lowest value. All were run with six levels, not always representing equal increments, because of range differences in data.

The Si/Al map series for the stratigraphic units as well as total sequence and total Ohio Shale are shown in Figure 65. Average values used for total sequence may vary from an average of 25 samples to an average of 75 samples, depending on the thickness of the well sequence involved.

3. Minerals Analyzed and Mineralic Ratios Studied

The 13 minerals analyzed are shown in Table 6 with simple statistics for minerals and mineralic ratios. Chemical formulas are shown in Table 7 and Table 8 shows ratio definitions.

4. Computer-drawn Maps on Mineralic Ratios

Computer-drawn maps for the mineralic ratios, using average values for the total stratigraphic sequence are shown in Figures 66, 67, 68, 69, and 70. The darkest printout is the highest value area, the lightest printout being the lowest. Increments are not always equal because of constraints on computer mapping of closely spaced lines. Computer maps were run as a check on hand-contoured maps. (See Analysis of Data section)

E. Production Studies from Final Open Flow Data from approximately 4750 wells.

The areas of Upper Devonian Ohio Shale gas production in eastern Kentucky are shown in Figure 71.

1. Distribution of Data Points

The locations of the approximately 4750 wells from which final open flow data were supplied by Kentucky-West Virginia Gas are shown in Figure 72. It is not intended that the well numbers be legible! Admittedly, there is some structure to the data distribution, but over-all the density averages about 5 wells/square mile. Density of points may go as high as 20 wells/square mile. It was decided at the onset of the study, because of apparent complexities of the field, to use all data obtained. During the contouring procedures, by hand (Figure 73, using all 4750 points) and by computer (Figure 74, using 4138 points) data points were rejected because of faulty location on supplied base maps, double well numbers, missing open flow data, and illegible data.

2. Hand Contoured Map (Figure 73)

The data points were so densely spaced that little interpretation went into hand contouring the data. The resulting configurations are concluded to be fairly reliable, in terms of representing the data used.

Contouring was done on a base map at a scale of approximately 1:100,000. This was reduced to a scale of 1:250,000. A three-level version of final open flow contours was color-coded, from which the directional trends discussed later were measured.

3. Computer-drawn Map (Figure 74)

Data points were given coordinates by the computer data processing section of the West Virginia Geological and Economic Survey under the direction of Mrs. Mary Behling. Sixteen computer-drawn map sections were run, the total compilation size of which was 8' x 16'. These map sections were reduced and compiled into a single map from which Figure 74 was hand-copied and coded at three levels like the hand drawn map. The resulting configurations tend to be rendered more orthogonally than the hand-contoured version (Figure 73). In the final computer mapping program used (ADMINMAP): 1) 2-3 points were averaged; 2) there was no overlapping of map strips; 3) areas were contoured rather than blocked; 4) paper was reversed to eliminate pattern; and 5) commencing with a value of 0.10 MMcf, increments used in mapping were 0.15, 0.25, 0.25, 0.25, 0.50, 0.50, 0.50, 0.25, 0.25, and 5.00 MMcf/day.

A histogram of the data (0.00- 2.00) is shown in Figure 75. A break is represented between frequency of 800 and 2000 because of the total length that segment would have. The data are not graphed past 2.00 on this scale because of scanty data occurrence in the

>2.00 MMcf/day section.

A second histogram of the data (0.00- 0.225) is shown in Figure 76 to show the finer structure of the frequency represented in that interval of open flow values. Finally, Figures 77a and 77b show a large scale graph of all data used in computer mapping.

Two cross sections taken through the hand-contoured and computer-drawn maps are compared (See Figure 105, Data Analysis section). There is a general similarity between the two curves, but sufficient offset and smoothing occurs to suggest that exploration studies should use hand-contoured maps rather than computer-drawn maps, or use a combination of both types.

4. Density of High Open Flow Wells

A data set very similar to that provided to the author was provided to James Griffith of mobile oil (1976) for analysis. See Figure 78. In the data set given Griffith the author connected all wells with values >= .5 MMcf/day where not contra indicated by lower open flow values. The resulting pattern is seen in Figure 79.

Griffith contoured the density of wells >=0.5 MMcf/day per 25 square miles and >=1.00 MMcf/day per 25 square miles. The contour values represent the general pattern of gas accumulation (Figure 80).

III. ANALYSES OF DATA

A. Open Flow

About 90% of eastern Kentucky gas wells are "shot", 9.9% are treated, and 0.1% are natural flow completions. Measurements on an 8 hour period following the shooting or well treatment are the basis of the open flow data used. It is not deemed necessary to separate data on the basis of the differences in well completion (Jenkins, 1977).

Three trend surface analysis programs were run first on the entire field and then on sections of the field. Figure 81 shows the first degree surface trends for these programs.

The fourth degree surface for the entire field, using a grid set of 417 equally spaced points, produces Figure 82. This may be compared with the plots of Griffith in Figure 80, which show the same basic NE-SW trend.

From the hand-contoured open flow map with 3 contour levels, Figure 83, trends of high production areas (Figure 84) and of low, or non-production areas (Figure 85) were traced. Although this is a subjective procedure, the close spacing of the data points used for the contouring suggests severe restrictions on the resultant configurations. Trends represent long axes of patterns. The low open flow traces are more subjective because of the larger spaces involved.

Polar plots of trend lengths were plotted for the high (Figure 86) and low (Figure 87) trends. A change in direction is noted with change in length of trend. Cumulative plots of high and high plus low are shown in Figure 88. Three major directions are repeatedly apparent: NW-SE, NE-SW, and E-W. These configurations may be compared with the polar plot from Long (1979) of Devonian shale composite fractures from outcrop (Figure 89). This latter work shows the NE-SW and NW-SE directions to be dominant in fracture trends at the outcrop. The E-W direction is conspicuously absent.

Even in early writings (Hunter, 1935; Thomas, 1941; Lafferty, 1941; McFarlan, 1943; and Billingsley, 1934) the gas production was interpreted as being dependent upon fracture occurrence (See Introduction). Thus, the trend traces of high open flow configurations and possibly those of the low trends (See Figures 84 and 85) may be regarded as probable fracture patterns. This might further suggest that the Ohio Shale sequence is diversely fractured throughout the field, presenting a "fracture facies" as described by Shumaker (1977). In a series of studies of natural fractures in cores from Martin, Perry, and Johnson counties, Evans (1979) has observed great diversity in fracture orientation in the shale sequence.

Different lithologies may be expected to show a differing degree of fracturing, and therefore, percentages of silt and sand to organic black mud should affect the intensity of fractures or fracture frequency. Thus, the "fracture facies" concept may be even more restrictive in terms of a preferred lithologic unit which may or may not in turn relate to a stratigraphic unit. Such a "fracture facies" could be independent of stratigraphy interpreted from natural radioactivity. We will return to this concept in considering the Analysis of Lithology Study results.

Table 9 shows a comparison of 1964 data and the present study in terms of total open flow, average open flow per well, and percent dry holes. Average per well has increased by 20 percent and dry holes have decreased by almost 10 percent. In 1964 Knott County shows the highest number of wells producing from the Devonian. See Table 10.

Based on 415 MMcf total recovery per well x 5000 wells the estimated recovery is approximately 2 trillion cubic feet of gas from the Devonian black shales in the field area for that number of wells.

B. Structure

Three main structural trends are apparent(Figure 14 and 15): north-south, east-west , and northeast-southwest. Table 11 shows the features, trends, and ages. North-south trends dominate from Precambrian through Mississippian time. East-west features are also prevelant from Precambrian through Mississippian with growth in the Rome Trough continuing to the Recent time. The northeast-southwest trend appears to become more dominant in Pennsylvanian time with domal structures (Pike County Uplift and Perry County Uplift) appearing probably in Mississippian and a known igneous intrusion in the Permian, with associated dikes.

The depth and continued displacement along and related to the Rome Trough basement feature is better brought into perspective with a three dimensional model based on Shumaker's (1977) interpretation of basement structure (Figure 90). The basement trough in the northern area is 14,000 feet or almost 3 miles deep (the northwest corner showing a depth of -2000 feet, deepening to -16,000 feet in the northwest). This is over four and one-half times the depth of the Grand Canyon at Toroweap, Arizona. By the Ammerman and Keller (1979) interpretation (Figure 11) the Floyd County Channel would intercept the Rome Trough at the same depth. These cratonic features and subsequent changes and developments of structural features may be expected to affect depositional characteristics and complexities. The black shale isopach values are greatest over the Floyd County

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Dec. 1979

Channel. This is also the area of complex intertonguing of the westward prograding deltaic facies with the organic muds. The geochemical data also suggests greater marine influence coming in from the southwest and slightly from the northeast; fresh water influence is suggested from the north, west, and east (See D. Geochemistry, page 45).

Fractures in black shale, like coal cleats, may relate to stress directions and basinal configuration. Although the Ohio Shale sequence shows an overall N-S strike in isopach contours, the present attitude of the black shales relative to the Fire Clay coal (Figure 91) suggests a northeast trending line of flexure along the eastern side of the eastern Kentucky syncline. The late Paleozoic uplift in the southeast hinged along this line. This hingeline also plunged slightly as it is followed northeastward and southwestward on each side of the Paint Creek Uplift, dividing the eastern Kentucky syncline into two basinal areas, one northeast and the other southwest of the Paint Creek Uplift. (Figure 5). Fracture zones and faults could be expected to relate to these movements and structures involved, and the fractures and faults could be expected to be reflected in production patterns (Figure 79), which do indeed show: 1) a northeast trending cut off and several linear, east, southeast radiating high production bands from a central intricate pattern over the nose of the Paint Creek Uplift (Figure 92 and computer map, Figure 74). Note: A radiating pattern of lineaments in the area of radiating high production trends has been recognized from Landsat by three independent workers since the completion of this study (Donahue, 1979).

The pattern, when viewed in 3-D (Figures 93 and 94) shows the NE-SW trend, as well as some of the other possibly radiating directions.

A polar plot of structural features and trends of high open flow may be seen in Figure 95. The east-west and northeast-southwest directions appear to show the greatest correlation.

C. Stratigraphy-Lithology

During Devonian time the North American continental plate was probably situated south of the equator with the Appalachian black shales being deposited at about S 35 degree latitude. (Figure 96; after Heckel and Witze, 1978, with permission). This reconstruction is based on carbonates and lithic paleoclimatic indicators, and appears as the cover of the publication entitled "The Devonian System" which resulted from the International Symposium on the Devonian in 1978 in Bristol, England. It may be noted that in this interpretation South America is very nearly convergent upon the North American continental plate margin in close proximity to the study area. A model of island-arc collision is favored for Upper Devonian time.

Also from Heckel and Witze, (1978) see Figure 97 which shows Upper, Middle, and Lower Devonian paleogeography. The study area location is noted in these figures by a rectangle.

The role of plate interactions in sedimentation is discussed by Sloss and Speed (1974), related to miogeosynclinal and eugeosynclinal sedimentation by Rogers (1971), and suggested by Provo (1977) to relate to understanding the black shale sedimentaiion. Discussion of causal agents outside the study area is beyond the scope of this work other than to acknowledge the framework of present concepts into which this study may fit.

In such a framework it is interesting to note the change in rate of basinal subsidence deduced from unit isopach maps relative to two bentonite layers. (Figure 98). The lower bentonite is possibly the Tioga Bentonite (but 50 feet into the chert and limestone) and the upper is here designated as the "Big Sandy" Bentonite.

The changing strike of the isopach map contours (Figure 94) is also of interest, and appears to change from a northeasterly direction to north-south to northwesterly, suggesting changes in basinal configuration.

From the lithology studies, Figure 99 shows histograms of observed fractures versus lithotypes, stratigraphic units, structure on top of Ohio Shale, and thickness of total shale. The highest degree of correlation is seen in mud-shale lithology, the middle Huron unit, -1000 to -1250' (below sea level) on Ohio Shale structure, and a thickness of 500 to 600 feet in total sequence. If the areal values of the fracture occurrence, shale thickness, and structure on the Ohio Shale are supperimposed, Figure 100 results. This suggests a high priority area (1) and second (2) and third (3) choices in terms of anticipated high open flow. The outlines of Griffith's contours of density of high producing wells are shown for comparison. From such a comparison, the mud-shale lithology is suggested as the "fracture facies" lithotype and the middle Huron unit as the stratigraphic unit in which such a lithotype is more common in the field area. Fracture facies may be expected to relate to other units in other areas or specific locales.

From Thomas (1951) an iscpach map of brown shale in the Prestonsburg Quadrangle, with the demarcation line between <0.1 MMcf and >0.1 MMcf open flow, is shown in Figure 100. The trend of the line is NNE across the quadrangle, diagonally across the 400-

500-foot isopachs of "brown shale." This trend relates closely to the trend of contours of percent brown silty mud-shale in Figure 40, the 90% line being very close to the above mentioned demarcation line. However, the values for the percent brown silty shale in Figure 40 drop off to the southeast, whereas the open flow values increase. The highly organic black shale increases to the south of the figure in question and the silt and sand increase to the east-northeast.

The 10 fracture/well contour in Figure 38 closely parallels the demarcation line and could suggest a fracture frequency limit of 10 fractures per well for >= 0.1 MMcf open flow, other factors being suitable.

The isopach anomalies in Figure 101 show thickness anomalies of 20-30 feet imposed on a basically N-S strike. These may be a result of erosion at the top of the Ohio shale over structural features, or "ponding" of black shale deposition in depresions on the epicontinental shelf terraces during sedimentation (Browning, 1935). There may have been some karst development in the underlying limestones. Because production has not appeared to show a 1:1 correlation with the individual closures in studies in the past (Thomas, 1951; Billingsley, 1934; Lafferty, 1941; Hunter, 1935 and 1964), recovery may rather be more complexly related to compaction fractures which are related to shale thins and thicks, silt-sand layers, and fine structure, and thus, not show absolute constraint by fine structural anomalies. A present study of detailed structure and relationships to gas occurrence is in progress (Lee, 1979).

The role of structural development along with the lithological differences is discussed under structural development in this section and in Summary and Conclusions.

Using a stepwise regression procedure for dependent variables D1, which is density of high producing wells >=.5 MMcf/day/25 square miles and D2, which is density of high producing wells >=1.0 MMcf/day/25 square miles and independent variables (fractures, structural depth on top of Ohio Shale, shale thickness, percent sandstone/siltstone in total sequence, carbonate percent, green shale percent, occurrence of redbeds, black shale thickness, brown shale percent, gray shale percent) the following relationships were observed:

1. D1 was best explained by fractures: R^2 = 83%

Adding redbed occurrence: R^2 = 92% No other variables met the 5% significance level for entry into the model.

2. D2 was best explained by fractures: R^2 = 64%

Adding brown shale % of total sequence: R^2 = 92%

Adding structural position: $R^2 = 96\%$ No other variables met the 5% significance level for entry into the model.

3. Table 10 shows the correlation coefficients.

Significant relationships at the 5% level are boxed.

Thus, conclusions from the lithology studies may be summarized as follows:

1. The samples studied indicate a shaly Berea-Bedford sequence in the southwest of the field with increasing silt and some sand to the east. The thickness appears fairly uniform.

2. The Ohio Shale shows a high shale content in the southwest with increasing silt and sand to the northeast, with a high silt-sand value area to the southwest of the field center. The clastic grain size increases to the northeast.

3. A higher carbonate zone trends northeast-southwest. Redbed occurrence follows the same trend. This may represent a higher area during Upper Ohio Shale deposition time or a preferential current direction bringing in detrital redbed fragments and following the incipient development of the eastern Kentucky syncline. This area also correlates with the thickest area of the "Corniferous" limestone, which suggests early basinal development.

4. Fractures, as observed from well cuttings and core data, and related to frequency of indicated horizons, appear to be most strongly related to:

a) mud shale lithology, b) middle Huron stratigraphic unit, c) 500-600 foot thickness of total shale, and d) -1000-foot to -1250-foot structural position on top of the Ohio Shale. Figure 101 shows the comparison outlines of areas using these correlations, and the configurations of Griffith's density of high producing wells (>= .5 MMcf/day/25 square miles and >= 1.0 MMcf/day/25 square miles). A non-subjective method of fracture identification is desirable. However, results from this study are promising in lieu of other means of fracture identification.

5. The more highly fractured well centrally located in Floyd County may penetrate a normal fault of approximately 75-150 feet on the west side of the Floyd County Channel. The Ohio Shale appears to be 75-150 feet short. The Huntersville Chert underlies the Ohio Shale section.

6. The Knott County well may have penetrated a shallow margin thrust fault.

7. Positive identification of all Ohio Shale members in cuttings is not feasible without other information. More studies using lithology, biostratigraphy, and radioactivity are needed in subsurface (similar to Swager's outcrop studies) to

better interpret the intricacies of shale stratigraphy in the Eastern Kentucky Field.

D. Geochemistry

Configurations of elemental percentages are compared with density of high producing wells (Figures 64, 102, and 80). Those showing similar configurations (Figure 63 for example), whether from high central values or low, are related in Table 13 to stratigraphic units.

Elements showing great similarity in map configuration are Al, Si, S, Mg, K, Fe, Ca,, and the ratio Si/Al.

The highest number of correlations is related to the lower Huron unit, followed closely by the upper Huron. The element showing the highest number of correlations is sulfur, followed closely by Mg, and then by both Al and the ratic Si/Al. Although Al and Si/Al showed these high correlations, Si alone, did not.

Mineralic ratios were interpreted in terms of paleoenvironment. The Kaolinite/Kaclinite + Illite Ratio #1 has been used in coal research (Renton, 1979; Negus-deWys and Renton, 1979). Based on this work the ratio of kaolinite to illite changes, depending upon the inferred depositional environment. Kaolinite is an indication of fresh water environments while illite becomes increasingly dominant as the environment becomes more "marine" or alkaline. In the southern Appalachian basin coals or the western coals, interpreted as having fresh water origins (lacustrine, alluvial plain), kaolinite makes up 70% or more of the clays. In the northern Appalachian basin, interpreted as being more "brackish," the ratio is about 50:50, while in the Illinois basin where coals accumulated in a more "marine" influence, the kaolinite represents about 30-40% of the clays. The terms "brackish" and "marine" are relative terms. The most marine conditions under which coal could be preserved would actually be brackish at best. Thus, the Kaolinite/Kaolinite + Illite ratio in this study is monitored as a possible indicator of marine influence, the shales being considered the product of a poorly preserved peat type of environment.

The Quartz/Quartz + Kaolinite + Chlorite + Illite Ratio #2 is basically a quartz-clay ratio. The relative abundance of quartz would be expected to increase as the clastic source is approached, i.e., greater proximity to land. This is the interpretaion applied to the data.

The Siderite/Calcite + Dolomite + Siderite Ratio #3, again is based on coal studies. Siderite is correlative with a fresh water-dominated environment.

This ratio parallels the Kaolinite/Kaolinite + Illite ratio, the siderite only appearing as a dominant carbonate phase when kaolinite represents 70% or more of the clays.

The role of diagenesis could be raised to complicate the picture, but at the present writing, it was decided to use the interpretation based on coal studies unless conflict was shown with other map interpretations, or a good basis for changing interpretation of this ratio was revealed (Smosna, 1979).

The Calcite/Calcite + Dolomite Ratio #4 is the classic carbonate ratio with increased dolomite reflecting near-shore, evaporative environments.

The Chlorite/Chlorite + Kaolinite Ratio #5 is also interpreted on the basis of coal study results. Based on coal studied, chlorite is a marine indicator. There does seem to be a variation in the relative abundance of the chlorite and kaolinite depending upon the depositional geochemistry. This ratio monitors the chlorite portion of the clay suite.

Table 12 shows the basic interpretations used in the mineralic ratio maps. When the highest and lowest values of all ratios are compiled on a master map, Figure 103 results. Stage 2 of interpretation is shown in Figure

104. No major conflict is observed in the compiled interpretation map. The north central section of the study area (Paint Creek Uplift) is dominated by the highest fresh water indication, non-alkaline, and close to clastic source, with the closest to clastic source value situated at the central southern extreme of this area. Fresh water areas are indicated east and west in the vicinities of the Pike County and Perry County uplifts. An area of marine influence extends from the southwest into the study area, with a slightly marine area indicated in the northeast. This trend may be related to the eastern Kentucky syncline development (see Figure 2) and shows interruption of this marine trend, and perhaps central blockage of marine water; similarly, the syncline is interrupted by the N-S interruption by the Paint Creek Uplift from the north.

The marine, clastic source area just to the southwest of the center of the field is an anomalous carbonate and clastic area, also shown in the lithology studies to show the largest number of fractures. Fracture filling probably contributes to the anomaly. The center of the field has been shown also in the lithology studies to be an area of intertonguing complexity of different shale types. The green shale appears to be emanating from the northeast, which coupled with the geochemistry would suggest fresh water transport. The brown shales appear to originate largely in the northwest, related through geochemistry to fresh water transport and clastic source. The indication of near-shore evaporative environment for the entire northwestern three-quarters of the area is suggestive of very shallow water deposition.

The southeast direction, from which later thrust and uplift occur, appears not to be strongly marine, but also not strongly fresh. Lack of data hampers further interpretation.

Marginal trends of computer-maps are computer-related distortion and the central area is thus more reliable. It should be mentioned that this is an ongoing study, in which 162 maps and 160 graphs have been produced to date. A proposal has been funded for further definitive interpretation and regional relationships.

Conclusions based on the geochemistry study to date include the following:

1) elemental inorganic geochemistry shows promise as an exploration tool for field development,

2) the Si/Al ratio of oxides, Al oxide, S and Mg oxide maps show the highest number of correlations with contoured densities of high producing wells,

3) the lower Huron shows the highest number of

correlations of elemental data with production; the upper Huron is a close second; the Three Lick shows the least correlation, and

4) mineralic ratios are best used for palecenvironmental interpretation, at the present stage of data analysis.

Stratigraphic unit tops need refinement from lithclogy studies and ratio interpretation should be further researched for more specific paleoenvironmenal implications.

E. Speculation

It is always tempting after an intensive study to speculate on posibilities with the fragmentary evidence at hand. When the structure, stratigraphy-lithology, geochemistry, and open flow data are all compared, gravity tectonics, driven by the uplift in the southeast and abutting against the Paint Creek Uplift, may explain an area following closely the basement Floyd County Channel, having 1) shorter and more intense fractures, 2) early gas migration to the area off the nose of the Paint Creek Uplift, 3) disruption of lithology patterns, 4) geochemical anomalies, 5) patchy sands in the Berea/Bedford, 6) high pressure in the center of the field, 7) a ghost thrust pattern on accordant summit levels, and 8) fracture facies more intense in the Huron where detachment is known to occur. The N-S trend in open flow trends occurs only in the low or non-productive areas outside the high open flow area.

Eastern flowing rivers from the central area off the Paint Creek Uplift are mentioned in older literature (Billingsley, 1934) as occurring in Berea/Bedford time. This may also account for "meandering" patterns of high open flow off the nose of the Paint Creek Uplift.

The contemporary residual in situ compresional stress is oriented E-W in eastern Kentucky and is suggested by Sybar and Sykes (1973) to be related to the driving mechanism of plate tectonics. This in situ stress could be expected to affect both the existing fracture patterns of the black shale, and induced patterns of fracture after "shooting" a well.

IV. SUMMARY AND CONCLUSIONS

Trends in the structural setting of the Eastern Kentucky Gas Field originate in the Precambrian with N-S, E-W, and NE-SW directions.

Basement tectonics, whatever the cause, appear to continue to play a role in basinal configuration, thin-skinned tectonics, and interaction of structural development throughout the Paleozoic history of the field. Sedimentation, facies relationships, and fracture development in turn are affected by one or more of these factors. The pattern was established early with the formation of the northeast trending Rome Trough in the area of the present-day eastern Kentucky syncline.

Basinal subsidence, during deposition of the Ohio Shale sequence, was preceeded by volcanic ashfalls (bentonite) during several intervals. Thicker shales, suggesting more rapid basinal subsidence, occurred in lower Huron time shortly after these ashfalls and again in Cleveland time following another period of volcanic ashfalls ("Big Sandy" bentonite). These thicker sequences are also blacker as a result of higher organic content. An obvious correlative question would be the possibility of volcanic activity preceeding the upper Huron blacker shales.

The source material for the organic black shales appears to originate largely from cratonic marginal areas to the north and west of the field area where it may be presumed, large swamp forests of Archaeopteris (Callixylon) existed. These tree-ferns, placed in the special class of Progymnospermopsida, reached a diameter of more than five feet.

How far into the inland sea these early giants of the Devonian swamps ventured is open to conjecture, but they probably did not grow in water deeper than 1-2 feet. The shallow, anoxic, inland seawater was teeming with green algae (Tasmanites) and brown algal forms, i.e., Protosalvinia, and the black shales show evidence of at least six other plants. Prevailing winds during the upper Devonian were from the east; related to present-day geography the prevailing wind direction would be from the northeast of the study area concentrating floating vegetation in the southwestern part of the basin against the cratonic margin. A similar condition presently exists in Lake Erie.

Detrital clays and silts, from the prograding deltas to the east and north, were deposited in complex intertonguing relationships with brown organic silts from the north and northwest and black muds from the northern and western cratonic swamplands. There may also have been contributions from the south. Ashfalls may have actually increased plant productivity after temporary damage or destruction. Organic soils were washed off the cratonic margin in fresh water along with fine clays. Erosion of such soils would also have taken place as the lower Huron seas transgressed the low-lying craton.

The Paint Creek Uplift emerged in a north-south trend in the northwestern part of the study area, doming the Ohio Shale, and interrrupting the earlier established synclinal structure (ancestral Rome Trough) of the northeast trending eastern Kentucky syncline. This uplift divided the syncline into a northern "basin" and a southern "basin". Fracturing of the Ohio Shale in radiating bands to the east and southeast probably accompanied this structural development.

Uplift and compression originating in the southeast in post-Devonian time, was hinged along the eastern Kentucky syncline, and elevated the southeastern two-thirds of the area to form the southeastern slope flank of the syncline. This tectonic movement raised the Ohio Shale sequence slightly in that area and was probably accompanied by a second series of fractures related to these stresses emanating from southeast of the study area. The lowest portion of the sequence (lower Huron) might be expected to show the greatest effect of tensional fractures from this movement.

This uplift imparted a gravity gradient toward the northwest so that decollement features related to gravity tectonics could be anticipated. The lower Huron Shale, the base of which is the zone of detachment in the southeast, could be expected to be the site of greatest disruption.

The most complex intertonguing of lithofacies occurs over the center of high gas production, which has long been known to be associated with fracture occurrence and siltier lithology.

Cross sections through open flow data compared with structure show a close correlation of high gas accumulation to general doming of the Paint Creek Uplift. (Figure 105).

On a more localized scale, the high open flow trends appear related to radially oriented bands of higher production, focussed on the nose of the Paint Creek Uplift, but also showing smaller subtrends, posssibly resulting from interaction of the southeastern uplift and later southeastern and eastern compressional forces with the Paint Creek Uplift (Figure 92). The postulated radiating permeable fracture zones related to the Paint Creek Uplift probably provided conduits for the major pattern of gas accumulation off the nose of the uplift. Circular trends are also apparent around this nose. High pressure zones in the shales are probably a result of the compressional and compactional relationships, coupled with the fracture conduits over the nose of the Paint Creek Uplift.

The eastern flank of the eastern Kentucky syncline demarcates the major area of higher open flow from the area of little economic production to the northwest. Gas may have escaped in this latter area because of fractures extending to the surface and probably related to growth of the Rome Trough.

Thus, the Eastern Kentucky Gas Field, a coalescence of many fields, appears to represent overall a highly complex structural-stratigraphic gas trap.

Certain inorganic geochemical elements appear to delineate gas accumulation and/or structure, and thus provide a tool for field development and exploration. (Figure 106). Mineral ratios present a basis for interpretation of paleoenvironmental conditions, which in turn may prove useful in development and exploration.

The shale reservoir of the Eastern Kentucky Field area appears to have been deposited in an area which was dominated by relatively fresh water, marginal, cratonic swamps. These swamps were periodically destroyed and the organic debris contributed to the black shales accumulating at the toe of the prograding delta from the east. Cyclic development of gray and black shales on a detailed scale (within members) as well as on a larger scale (stratigraphic members) in the Upper Devonian Ohio Shale sequence is especially apparent in the northeastern part of the field. It is evidenced in wireline logs, lithology, and geochemical graphs. This recognizeable cyclical sedimentation continued through most of the Upper Paleozoic reaching a climax in the Pennsylvanian time when the swamp development phase of a cycle is preserved as coal.

Possibly future field development could benefit from exploring trends relating to the two interacting structural patterns resulting from the intersection of the Paint Creek Uplift trend and the southeastern uplift trend. Blocks within the Rome Trough could individually be productive because of more intense fracturing along their margins (Schaefer, 1979). Production might also be sought from smaller structures off the nose of the Paint Creek Uplift, but of sufficient size to cause compactional fractures or fractures originating from tectonic stress associated with the development of the structure. The contemporary in situ compressional stress is oriented east-west, which is also the trend of the 1st degree surface from trend surface analysis based on open flow data. A statistical advantage in offset wells from older high producing wells could be based on this evidence. Clearly, fracing (hydrofrac, etc.) results should be expected to have such a preferential direction and such information plus lithology and fracture frequency trends could be of use in bifurcating (trifurcating, etc.) in drilling wells.

The silt-clay ratios appear to play an important role in defining the best production in the field, and where possible, following these ratios may enhance drilling success. The 90% line for "percent clay of total sequence" runs approximately through the center of high density of high open flow values. The 50:50 silt:sand ratio passes N-S through the center of high production. These lines should be utilized in exploration.

The 10/well fracture frequency contour, parallels the greater than 0.1 MMcf open flow demarcation on the northwestern margin of the field. This is probably not fortuitous that such a minimum frequency of fracture horizons within a well relates to higher open flow. The fracture frequency pattern alone would also suggest extending exploration to the southwest. However, thickness of organic black shale diminishes rapidly in that direction so that will be a limiting factor to exploration in that direction.

The stratigraphic nomenclature of the Ohio Shale places the black bituminous Cleveland Member above the gray Chagrin Member, which in turn overlies the black Huron Member, which is very similar in lithology to the Cleveland. The upper portion of the Ohio Shale is a complex intertonguing of shales from primarily different source areas: grays and greens representing for the most part, uplift and distal deltaic sedimentation from the east and northeast, and black and brown resulting from encroachment and destruction of cratonic swamp margins by the shallow sea primarily from the west and northwest with some addition from the southeast. As such, the Cleveland and Huron Members are part of the same black lithofacies as are the gray and green lithofacies of the, again, Cleveland, Three Lick, and

Huron units. Gray silty tongues in the Cleveland can be traced eastward toward the source area where they increase in thickness, as can black tongues usually be traced toward the craton to the north and west.

A revamping of the nomenclature is thus suggested, based on lithofacies, source relationship, as well as biostratigraphic basis. The true depositional relationships of this time-transgressive sequence are not represented in the present nomenclature. A suitable and acceptable solution represents a major endeavor by itself.

V. SUGGESTED FUTURE PROBLEMS FOR STUDY

Other problems besides that of stratigraphic nomenclature raised by the present study include:

1. Study of black shale-coal as a continuum in paleoenvironments in terms of sedimentation, geochemistry, and energy dynamics (proposal in preparation),

2. Analysis of structure using 4200 + wells above and below the Ohio Shale sequence, and relationships to open flow data (study in progress),

3. Lithotypes in the Eastern Kentucky Field area and relationships to adjacent areas (pilot study on 700 thin sections funded and in progress),

4. Detailed production decline studies on segments of the field, and relationships to other parameters,

5. Detailed geochemical analysis of stratigraphic units and relationships to natural radioactivity and lithofacies (proposal funded for first year of a 2-year study),

6. Relationships of geological development of the Eastern Kentucky Gas Field to continental plate collisions and subduction,

7. Relationships of bentonite occurrence to basinal configuration and sedimentation; is there another bentonite zone beneath the upper Huron black shale; what effects did bentonite have on plants on

land and sea,

8. What Devonian plants contributed to gas formation, their habitat, evolution, etc.,

9. Into what depth(s) of water did the Upper Devonian black shales settle and what was their transport history,

10. How does the uranium content change across the field; what is the relationship to organics; what amount of gold exists in the shales,

11. Could elemental geochemistry on a finer scale be useful in exploration; could it be used in a mobile unit (under study),

12. Assuming gas is produced from fractures, what other methods could be used for detection: gas 'snoopers' (U.S. Army equipment), infra-red, plant changes, low altitude air surveys, shallow seismic (under study); would lichens be subject to gas emanations and, thus be natural fracture indicators,

14. Instead of cryogenics, why not "hot" wells, where a heat source (or differential) is used to encourage gas release from shales,

15. A more regional tie-in of present study with surrounding areas (study initiated),

16. Study the true range vertically and horizontally of <u>Protosalvinia</u>, and possible significance of its restricted zones,

17. Where are the "zillicns" cf spores (homosporous and heterosporous) that the large tree-fern, <u>Archaeopteris</u>, must have produced,

18. Are fish found in Ohio black shale in the state of Kentucky as they are in Ohio black shale in the state of Ohio; if not, why nct,

19. What is the stratigraphic relationship of the Boyle to the Huntersville,

20. Are there other bentonities in the Ohio Shale sequence and where are the source volcanoes; what kind of emissions,

21. Are there unrecognized erosional horizons within the shales,

22. What are the current directions for gray, green, black, and brown shales; what are the differences in each member of the Ohio Shale sequence,

23. Could the black shale be primarily eroded soil from the craton (as suggested as cne possibility in this paper),

24. How extensive is channelling in the black shales ; what are the directions and locations of channels,

25. A complete mica study along with other mineral contaminants in the lithology; possibility of igneous intrusions in the field area,

26. Is there a recognizeable porosity difference (which may be the result of the silt or sand content) related

to the demarcation of greater than 0.1 MMcf per day open flow, and that can be determined from wireline logs in combination (density logs, radioactivity, etc.),

27. Investigate Devonian cyclic sedimentation as a precursor to Carboniferous coal swamps (as suggested in this paper); causes common to both,

28. Tidal differences in the Upper Devonian and possible effects on sedimentation, including deltas, and

29. Could gravity tectonics driven by the southeastern uplift be the basic cause, in an area following the Floyd County Channel, for: 1) increased and shorter fractures, 2) early gas migration to the area off the Paint Creek Uplift nose, 3) disruption of lithology patterns, 4) geochemical anomalies, problems in log correlation, 5) patchy sands in the Berea/Bedford, 6) high pressure in the center of the field, 7) "thrust" pattern on accordant summit levels, and 8) fracture facies more intense in the Huron where detachment is known to occur.

TABLE 1 STRATIGRAPHIC UNITS IN STUDY AND RELATIONSHIPS TO NEW ALBANY SHALE AND CHATTANOOGA SHALE (after Swager, 1978, Provo, 1977, Lineback, 1968, Miller, 1965, McFarlan, 1943)

System	Series	Units of New Albany Shale in S.IN.-W.KY.		Units of Ohio Shale in OH.-E.Ky.			Units of Chattanooga Shale in W.VA.-E.TENN.	
Miss.	Lower Miss.	Rockford Limestone		Sunbury Shale			Big Stone Gap Member	CHATTANOOGA SHALE
Miss.	Lower Miss.	Jacob's Chapel Bed Henryville Bed Underwood Bed Falling Run Bed	NEW ALBANY SHALE	Bedford Berea Sequence			Big Stone Gap Member	CHATTANOOGA SHALE
DEVONIAN	UPPER DEVONIAN	Clegg Creek Member	NEW ALBANY SHALE	Cleveland Shale		OHIO SHALE	Big Stone Gap Member	CHATTANOOGA SHALE
DEVONIAN	UPPER DEVONIAN	Camp Run Member	NEW ALBANY SHALE	Three Lick Bed	Partial Chagrin Shale Equivalent	OHIO SHALE	Middle Gray Siltstone Member	CHATTANOOGA SHALE
DEVONIAN	UPPER DEVONIAN	Morgan Trail Member	NEW ALBANY SHALE	Upper Member Middle Member Lower Member	HURON SHALE	OHIO SHALE	Lower Black Shale Member	CHATTANOOGA SHALE
DEVONIAN	UPPER DEVONIAN	Selmier Member	Central Ky.	Olentangy Shale			Lower Black Shale Member	CHATTANOOGA SHALE
DEVONIAN	UPPER DEVONIAN	Selmier Member	Boyle ls./ch.	Marcellus Shale			Lower Black Shale Member	CHATTANOOGA SHALE
DEVONIAN	Mid. Dev.	Blocher Member		Onondaga Limestone/ Huntersville Chert/ Needmore Shale			Absent	

<table>
<tr><td colspan="4">Bedford-Berea Sequence</td></tr>
<tr><td colspan="3">Cleveland Shale
200 API units
Brownish-black, organic-rich shale with phosphate nodules near top.</td><td rowspan="5">OHIO SHALE</td></tr>
<tr><td colspan="2">Three Lick Bed
3-4 closely spaced negative deviations (less than 200 API units) on gamma ray curve
Interbedded brownish-black and greenish gray shales or mudstones (Provo, 1977).
Limestone with cone-in-cone may be present.</td><td>Partial Chagrin Shale Equivalent</td></tr>
<tr><td colspan="2">Upper Member
100-200 API units; massive brownish-black shale</td><td rowspan="3">HURON SHALE</td></tr>
<tr><td>Middle Member</td><td>Brownish-black and gray shales interbedded in lower half; Protosalvinia found in outcrop and core. Slightly less radioactive than Upper Huron Shale.</td></tr>
<tr><td>Lower Member</td><td>Brownish black, organic-rich shale with 1-4 thin zones of greenish gray to gray. 200 API units; 1-4 thin zones of lesser radioactivity.</td></tr>
</table>

Table 2. Stratigraphic Units Studied with General Gamma Ray Log Characteristics (Provo 1977) and Lithology.

PETROLOGY OF MUDROCKS
(Folk, 1974)

" Mudrock (word coined by Ingram) is a general term used herein to cover those Terrigenous rocks that contain more than 50 percent silt and/or clay. The most obvious division of mudrocks is on the basis of texture and structure:" (Folk, 1974)

Grain size of mud fraction	Soft	Indurated, non-fissile	Indurated, fissile
Over 2/3 silt	silt	siltstone	silt-shale
subequal silt and clay	mud	mudstone	mud-shale
over 2/3 clay	clay	claystone	clay-shale

Table 3. Mudrock Terminology of Folk (1974).

LITHOLOGY SYMBOLS

	Sandstone	Y	Plant Fragments
	Siltstone	P	*Protosalvinia*?
R	Redbeds	T	*Tasmanites*
	Limestone	→	Slickensides
	Dolomite	f	Fractures
	Pyrite	S	Spar
/\/\	Spicules?	g	Gouge
	Pseudo-oolites	μ	Microspores
/////	Bedding		
?	Missing Sample		
	Shales B-Black BR-Brown G-Gray GR-Green		

Table 4. Lithology Symbols for Cross Sections.

SIMPLE STATISTICS FOR CHEMICAL ELEMENTS

Variable	Weight Percent oxide (except Sulfur)			Variance	Coefficient of Variance
	Minimum	Maximum	Mean		
MN	0.016	0.500	0.051	0.001	66.789
FE	3.590	20.150	8.519	2.679	19.214
S	0.051	8.258	2.364	0.907	40.272
ZN	0.001	0.106	0.013	0.000	72.342
SR	0.000	0.064	0.004	0.000	109.953
NA	0.149	0.730	0.661	0.004	9.660
MG	0.733	4.157	1.428	0.171	29.007
AL	6.000	18.120	14.206	3.333	12.851
SI	48.000	78.300	55.103	7.912	5.105
P	0.102	0.962	0.138	0.009	70.618
K	0.401	8.460	3.354	0.438	19.720
CA	0.155	32.985	1.252	12.565	283.140
TI	0.230	1.160	0.931	0.020	15.043
Si/Al RATIO	2.829	12.102	3.982	0.776	22.113

Coefficient of Variance: Highest   Least

Table 5. Simple Statistics for Chemical Elements.

SIMPLE STATISTICS FOR MINERAL DATA

VARIABLE	Percent Total Integrated Intensity*			Variance	Coefficient of Variance
	Minimum	Maximum	Mean		
ILLITE	0.0	91.4	52.3	189.2	26.308
CHLORITE	0.0	1.9	0.7	0.1	50.586
QUARTZ	4.0	83.3	33.7	119.6	31.085
KAOLINITE	0.0	13.0	0.5	3.2	374.000
SZOMOLNOKITE	0.0	2.2	0.0	0.1	664.617
CALCITE	0.0	68.9	1.3	42.9	522.579
ORTHOCLASE	0.0	2.0	0.0	0.0	469.630
ANHYDRITE	0.0	1.1	0.1	0.1	277.298
PLAGIOCLASE	0.0	2.7	0.9	0.2	42.371
BASSANITE	0.0	4.0	1.9	0.5	36.698
DOLOMITE	0.0	70.5	1.7	67.1	475.066
SIDERITE	0.0	17.5	2.2	2.6	72.945
PYRITE	0.0	13.1	4.8	15.6	49.622
RATIO 1	0.0	100.0	1.3	42.8	515.179
RATIO 2	4.4	100.0	39.3	160.1	32.197
RATIO 3	0.0	100.0	78.7	717.6	34.045
RATIO 4	0.0	100.0	9.1	586.3	267.249
RATIO 5	0.0	5.5	1.2	0.3	46.639

*May be considered numerically equivalent to weight percent

Table 6. Simple Statistics for Minerals and Mineralic Ratios.

CHEMICAL FORMULAS FOR MINERALS

ILLITE	$(H_30,K)_y\ (Al_4 \cdot Fe_4 \cdot Mg_6)\ (Si_8 - \cdot Al_y)\ 0_{20}(OH)_4$ where $y < 2$, usually $y = 1$-1.5
CHLORITE	$(Mg, Fe^{+2}, F^{+3})_6AlSi_30_{10}(OH)_8$
QUARTZ	SiO_2
KAOLINITE	$Al_2Si_2O_5(OH)_4$
SZOMOLNOKITE	$FeSO_4 \cdot H_2O$
CALCITE	$CaCO_3$
ORTHOCLASE	$KAlSi_3O_8$
ANHYDRITE	$CaSO_4$
PLAGIOCLASE	$(Na, Ca)Al(Si,Al)Si_2O_8$
BASSANITE	$CaSO_4 \cdot 1/2H_20$
DOLOMITE	$CaMg(CO_3)_2$
SIDERITE	$FeCO_3$
PYRITE	FeS_2

Table 7. Chemical Formulas for Minerals.

RATIO DEFINITIONS

RATIO 1 $$\frac{\text{KAOLINITE}}{\text{KAOLINITE + ILLITE}}$$

RATIO 2 $$\frac{\text{QUARTZ}}{\text{QUARTZ + KAOLINITE + ILLITE + CHLORITE}}$$

RATIO 3 $$\frac{\text{SIDERITE}}{\text{CALCITE + DOLOMITE + SIDERITE}}$$

RATIO 4 $$\frac{\text{CALCITE}}{\text{CALCITE + DOLOMITE}}$$

RATIO 5 $$\frac{\text{CHLORITE}}{\text{CHLORITE + KAOLINITE}}$$

Table 8. Ratio Definitions.

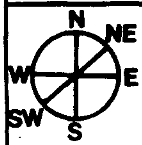
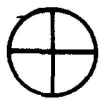
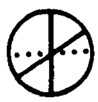
Jane Negus-de Wys
WVU Dept. of Geology and Geography
Dec. 1979

DATA	TOTAL OPEN FLOW	AVERAGE PER WELL	PERCENT DRY HOLES (.06 MMcf/DAY)	AVERAGE TOTAL RECOVERY PER WELL
1964 (Hunter) 4205 wells	1,450 MMcf	.342 MMcf	13	405 MMcf
1978 (de Wys) 4143 wells	1,711 MMcf	.413 MMcf	11.8	415 MMcf

Table 9. Comparison of 1964 (Hunter) Open Flow and this Study.

COUNTY	PERCENT OF TOTAL GAS WELLS PRODUCING FROM DEVONIAN	% DRY HOLES (<.06 MMcf/DAY)
Knott	78.3 (highest %)	9.2
Magoffin	6.3	32.5 (highest %)

Table 10. Counties with Highest and Lowest Open Flow Based on 4205 Wells (Hunter 1964)

Symbol Summary	Age	Feature	Trend N-S	Trend E-W	Trend NE-SW	Dome
	Precambrian	Rome Trough		x		
		Floyd County Channel	x			
		New York-Alabama lineament			x	
	Cambrian-Ordovician	Waverly Arch (east)	x			
		Rome Trough		(x)		
		Growth Faults		x	?	
	Silurian-Devonian	Cincinnati Arch	x			
		Eastern Kentucky Syncline			x	
	Mississippian	Paint Creek Uplift	x			
		Waverly Arch (west)	x			
		Pike County Uplift				x
		Perry County Uplift				x
	Pennsylvania	Eastern Ky. Syncline			(x)	
		Pine Mountain Thrust			x	
	Permain	Igneous Intrusion (Woodward Fault Zone)		associated with E-W		x
		Surface Dikes (Woodward Fault Zone)				

(x) = greatest movement or development

Table 11. Trends and Ages of Structural Features in the Eastern Kentucky Gas Field Area.

STATISTICAL ANALYSIS SYSTEM

CORRELATION COEFFICIENTS / PROB !R! UNDER HO:RHO=O / NUMBER OF OBSERVATIONS

	D1	D2	F	STRU	THICK	SS.SLT	O_3	GREEN	SH	R	BLK	BR	GRN
D1	1.00000 0.0000 7	0.94827 0.0039 6	0.91249 0.0041 7	0.37394 0.4086 7	-0.03624 0.9385 7	-0.09627 0.8340 7	0.09781 0.8348 7	0.09554 0.8385 7	0.09467 0.8400 7	0.19476 0.6756 7	0.47123 0.2858 7	-0.28196 0.5401 7	0.02922 0.9504 7
D2		1.00000 0.0000 6	0.79768 0.0573 6	-0.12742 0.8099 6	0.21759 0.6788 6	-0.19347 0.7134 6	0.00003 1.0000 6	0.32981 0.5232 6	0.18328 0.7282 6	0.10227 0.8471 6	0.50728 0.3044 6	-0.51729 0.2933 6	-0.00869 0.8673 6
F			1.00000 0.0000 7	-0.62674 0.1366 7	0.01572 0.9733 7	-0.02853 0.9516 7	0.17562 0.7061 7	-0.04941 0.9162 7	0.03118 0.9471 7	0.48867 0.2658 7	0.27429 0.5517 7	-0.04281 0.9274 7	0.04818 0.9183 7
STRU				1.00000 0.0000 7	0.01637 0.9722 7	-0.02186 0.9629 7	-0.08652 0.8537 7	0.03065 0.9480 7	0.01057 0.9821 7	-0.41219 0.3581 7	-0.20766 0.6550 7	-0.19755 0.6711 7	-0.23692 0.6090 7
THICK					1.00000 0.0000 7	-0.08801 0.8512 7	-0.07028 0.8810 7	0.80387 0.0293 7	0.08133 0.8624 7	0.36356 0.4228 7	0.00703 0.9881 7	-0.60940 0.1463 7	-0.28995 0.5282 7
SS.SLT						1.00000 0.0000 7	0.97501 0.0002 7	-0.26922 0.5593 7	-0.99982 0.0001 7	0.02919 0.9505 7	-0.72244 0.0667 7	-0.15200 0.7449 7	0.79581 0.0323 7
CO_2							1.00000 0.0000 7	-0.28395 0.5371 7	-0.97481 0.0002 7	0.15248 0.7441 7	-0.68439 0.0899 7	-0.16235 0.7280 7	0.75147 0.0515 7
GREEN								1.00000 0.0000 7	0.25832 0.5759 7	-0.07048 0.8806 7	0.45626 0.3035 7	-0.82428 0.0226 7	-0.24988 0.5889 7
SH									1.00000 0.0000 7	-0.01870 0.9683 7	0.71640 0.0701 7	0.16776 0.7192 7	0.79714 0.0318 7
R										1.00000 0.0000 7	-0.37963 0.4009 7	0.26670 0.5632 7	-0.36631 0.4190 7
BLK											1.00000 0.0000 7	-0.28238 0.5395 7	-0.26567 0.5647 7
BR												1.00000 0.0000 7	-0.15812 0.7349 7
GRN													1.00000 0.0000 7

- D1 — Density of High Producing Wells 0.5 MMcf/Day/25 sq. mi.
- D2 — Density of High Producing Wells 1.0 MMcf/Day/25 sq. mi.
- F — Fractures
- Stru — Structure on Ohio Shale
- Thick — Thickness of Total Shale Sequence
- Ss,Slt — Percentage of Sandstone and Silt in Total Sequence
- CO_3 — Percentage of Carbonate in Total Sequence
- Green — Percentage of Green Shale in Total Sequence
- Sh — Percentage of Shale in Total Sequence
- R — Percentage of Redbeds in Total Sequence
- Blk — Percentage of Black Shale in Total Sequence
- Br — Percentage of Brown Shale in Total Sequence
- Grn — Percentage of Green Shale in Total Sequence

Table 12. Correlation Coefficients for Lithology Study. Highest Degrees of Correlation are Boxed. Others are not Significant at 95% Level.

CORRELATION OF COMPUTER MAPS WITH CONTOURED DENSITY OF HIGH PRODUCING WELLS									
		Elements (all oxides except Sulfur)							Totals
Units	Oxides of Si/Al Ratio	Al	Si	S	Mg	K	Fe	Ca	
Berea-Bedford	+	+		+	+	+			5
Cleveland	0	+		+	+	+			5
Three Lick		0	+	+					3
Upper Huron	+	0	+	+	0	0			6
Middle Huron		+		0+	+			+	4
Lower Huron	+	0		+-	+	0	0	+	7
Total Sequence	+			+-	+		0	+	5
Ohio Shale	+			+-	+		0	+	5
Totals	6	6	2	8	7	4	3	4	

Table 13. Correlation of Computer Maps with Contoured Density of High Producing Wells.
+ Means a High Map Value Correlation
0 Means a Low Map Value Correlation
+- is Correlation with the Second Highest Map Value
Blank is no Correlation with Highest and Lowest Map Values

RATIO	ENVIRONMENT	RATIO MEANING
1. $\frac{Ka}{Ka + Ill}$	>Ka = fresh water >Ill = marine or alkaline influence	>Ratio—fresher water <Ratio marine alkaline
2. $\frac{Q}{Q + Ka + Ill + Chl}$	>Q = clastic source	>Q >Ratio >Ratio—closer to clastics
3. $\frac{Sid}{Cal + Dol + Sid}$	>Sid = fresh water	>Ratio—fresher water
4. $\frac{Cal}{Cal + Dol}$	>Dol = near shore evaporative environment	<Ratio—near shore evaporative environment
5. $\frac{Chl}{Chl + Ka}$	Chl = marine indicator	>Ratio—more marine

Table 14. Environmental Interpretations of Mineralic Ratios.

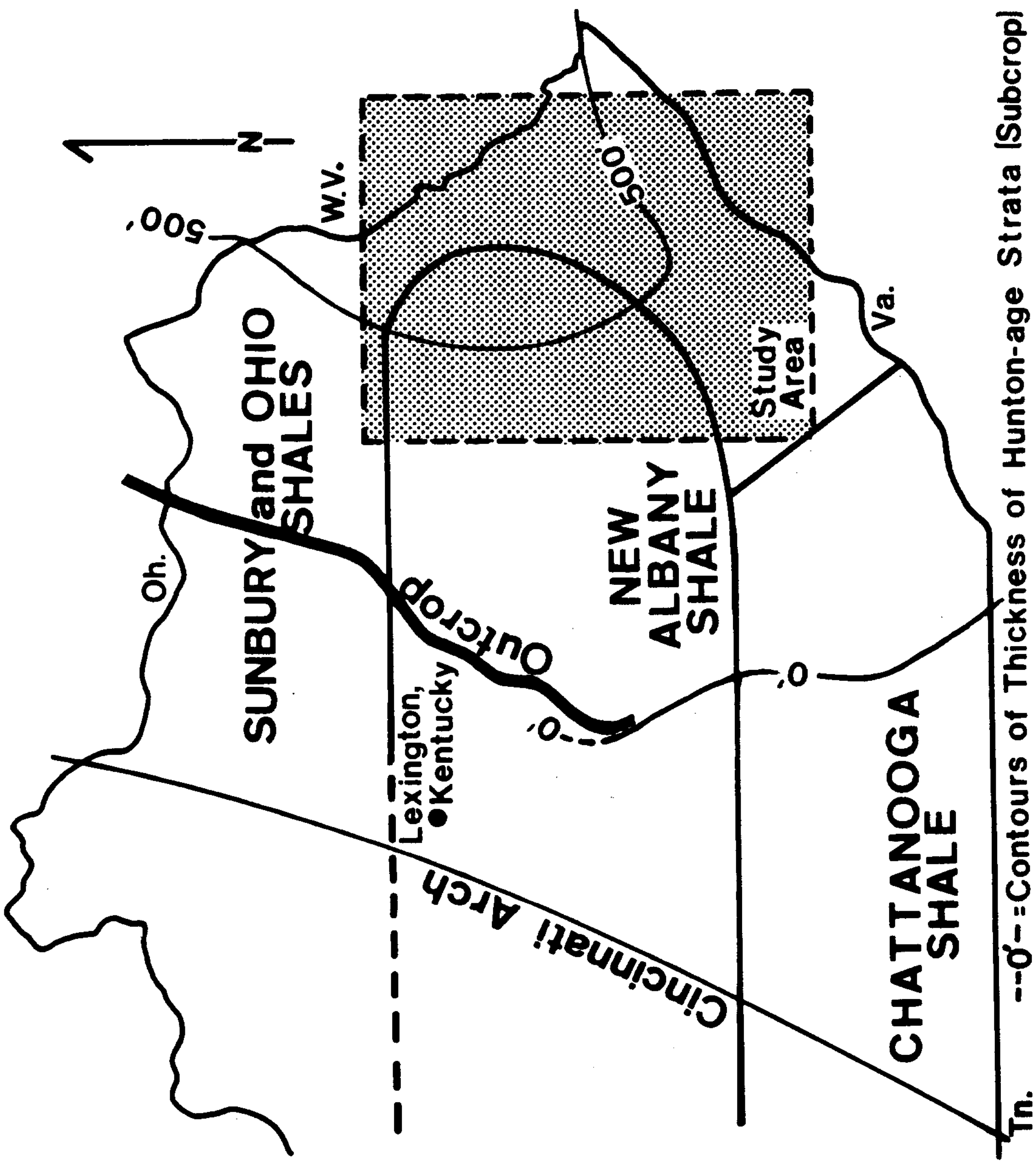


Figure 1. Location of study area and U.S.G.S. formational terminology (after Swager, 1978). Isopach lines (after Weaver and McGuire, 1973)

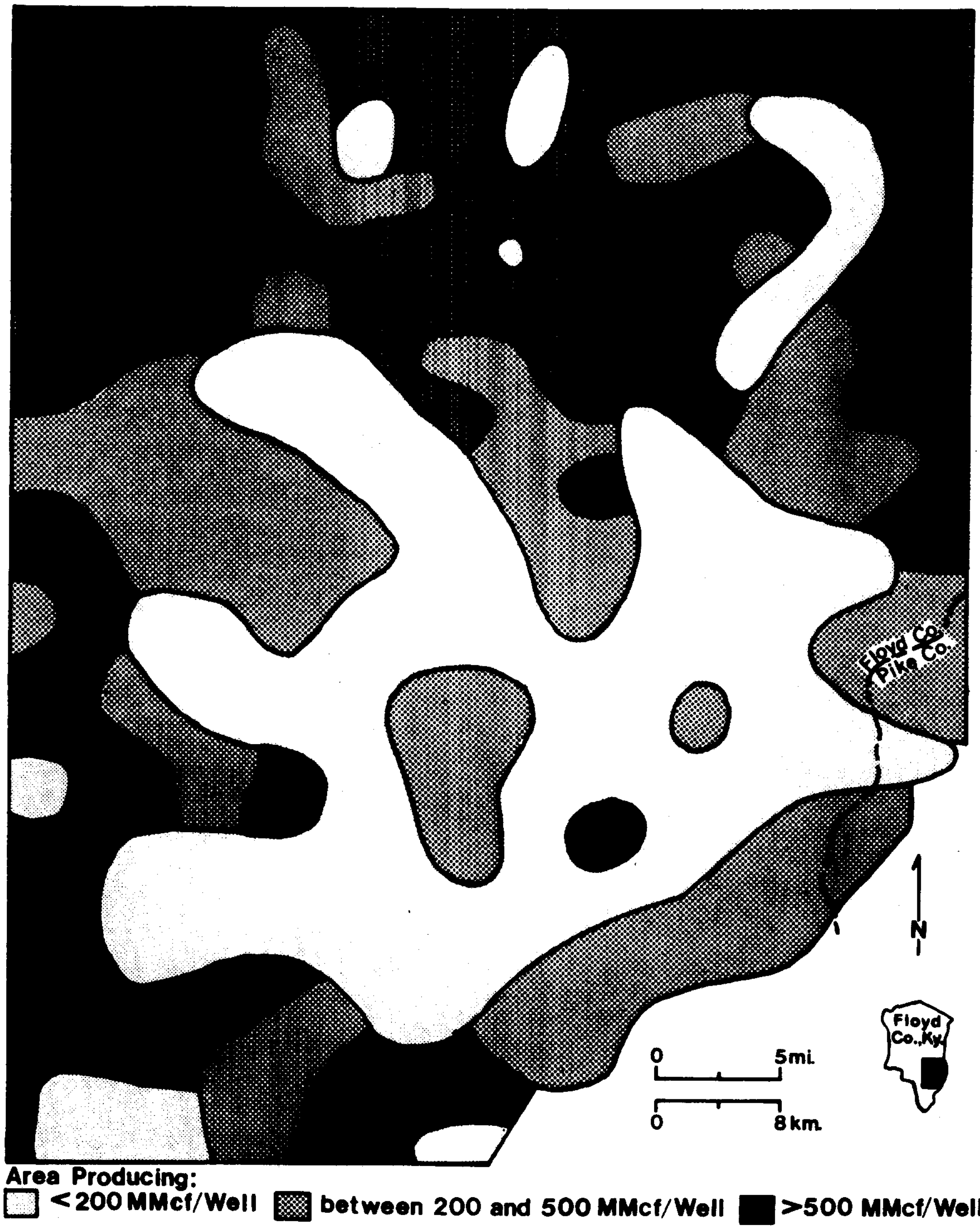


Figure 2. Pattern of gas recovery in a portion of Floyd County, suggesting recovery from fractures (after Hunter and Young, 1953).

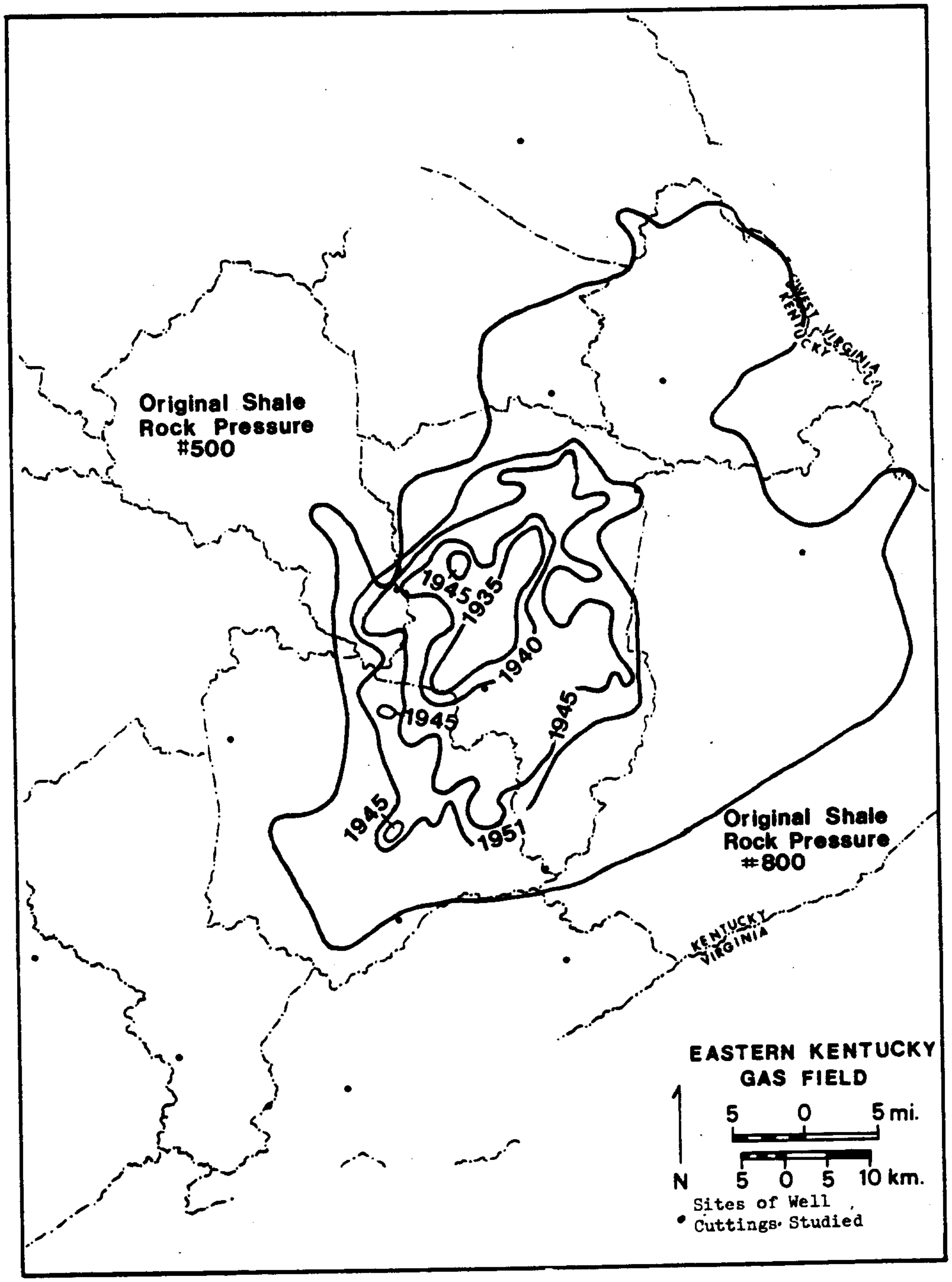


Figure 3. Rock shale pressure decline of 200# contour from 1935-1951 (after Hunter and Young, 1953).

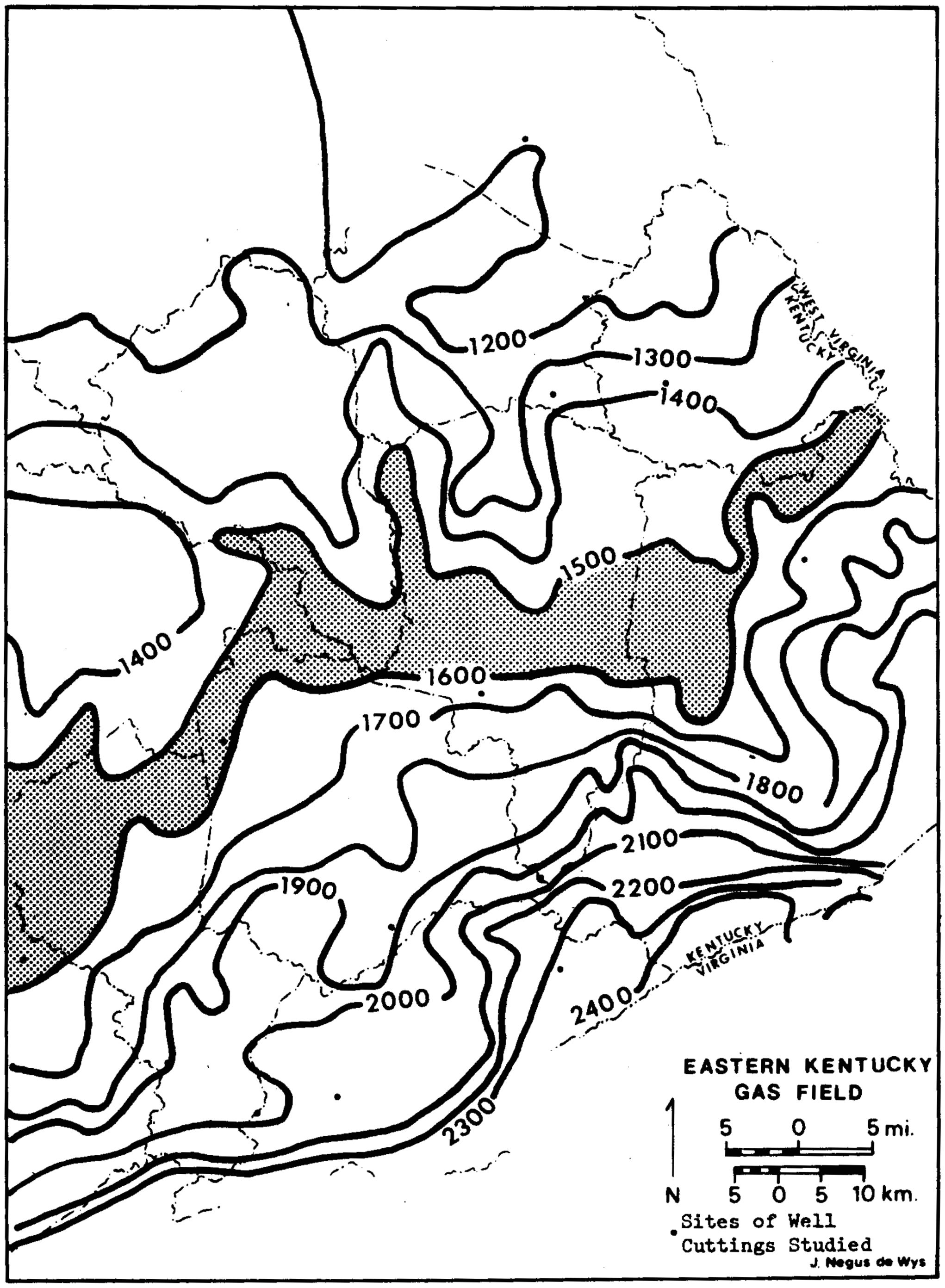


Figure 4. Accordant summit levels (after McFarlan, 1943).
Shaded area shows E-W central trend of contours.

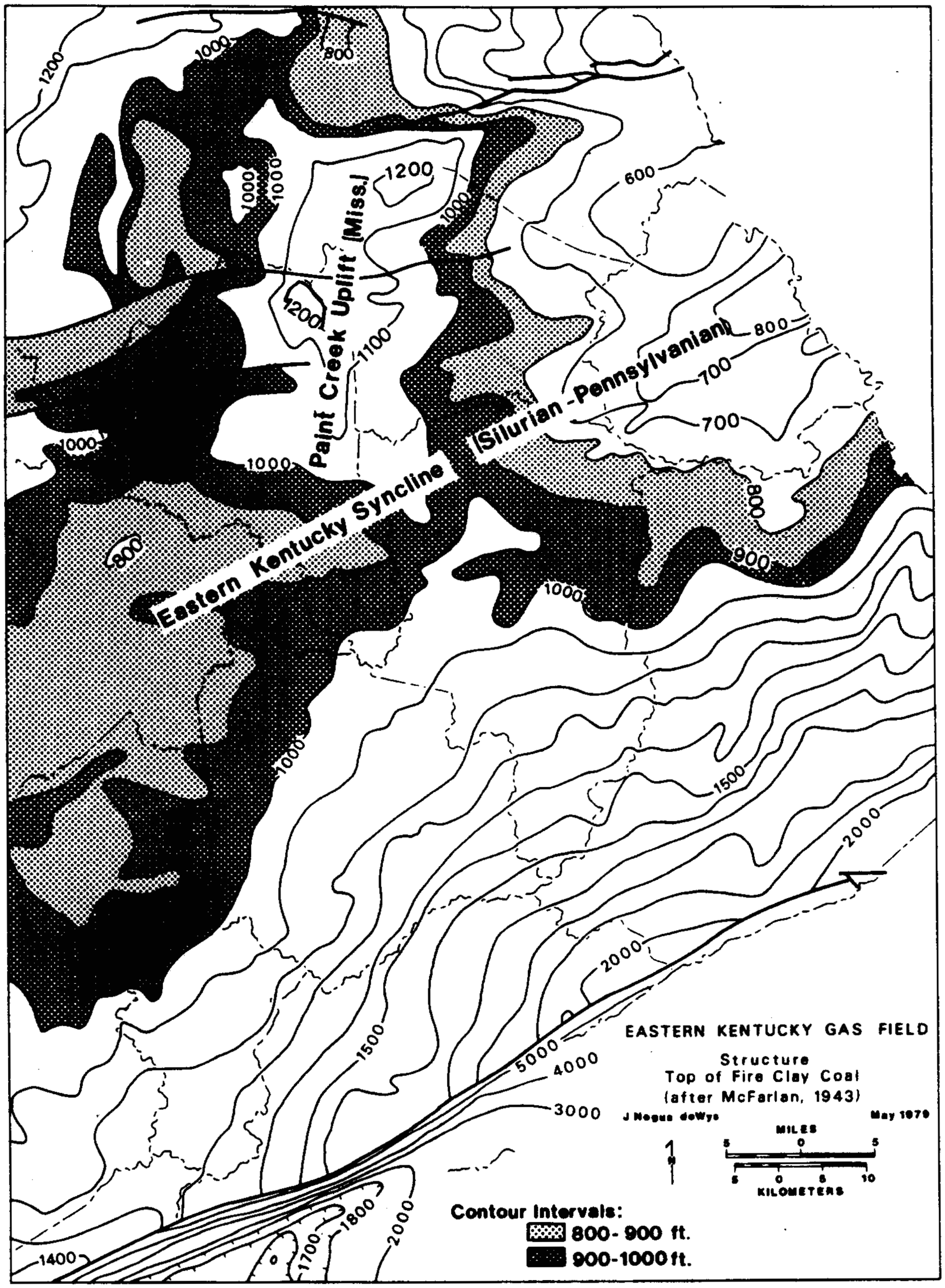


Figure 5. Structure on top of the Fire Clay coal (after McFarlan, 1943). Note: Northeast-southwest trend of syncline interrupted by the N-S trend of the Paint Creek Uplift; the northeast basin is deeper than the southwest basin; this is the area (NE) where the "Corniferous" limestone isopach suggests an early basin; and this northeastern area is suggested by geochemistry to be an area of marine tidal influence. See Figures 48 and 104. Age of structural development is indicated in parentheses.

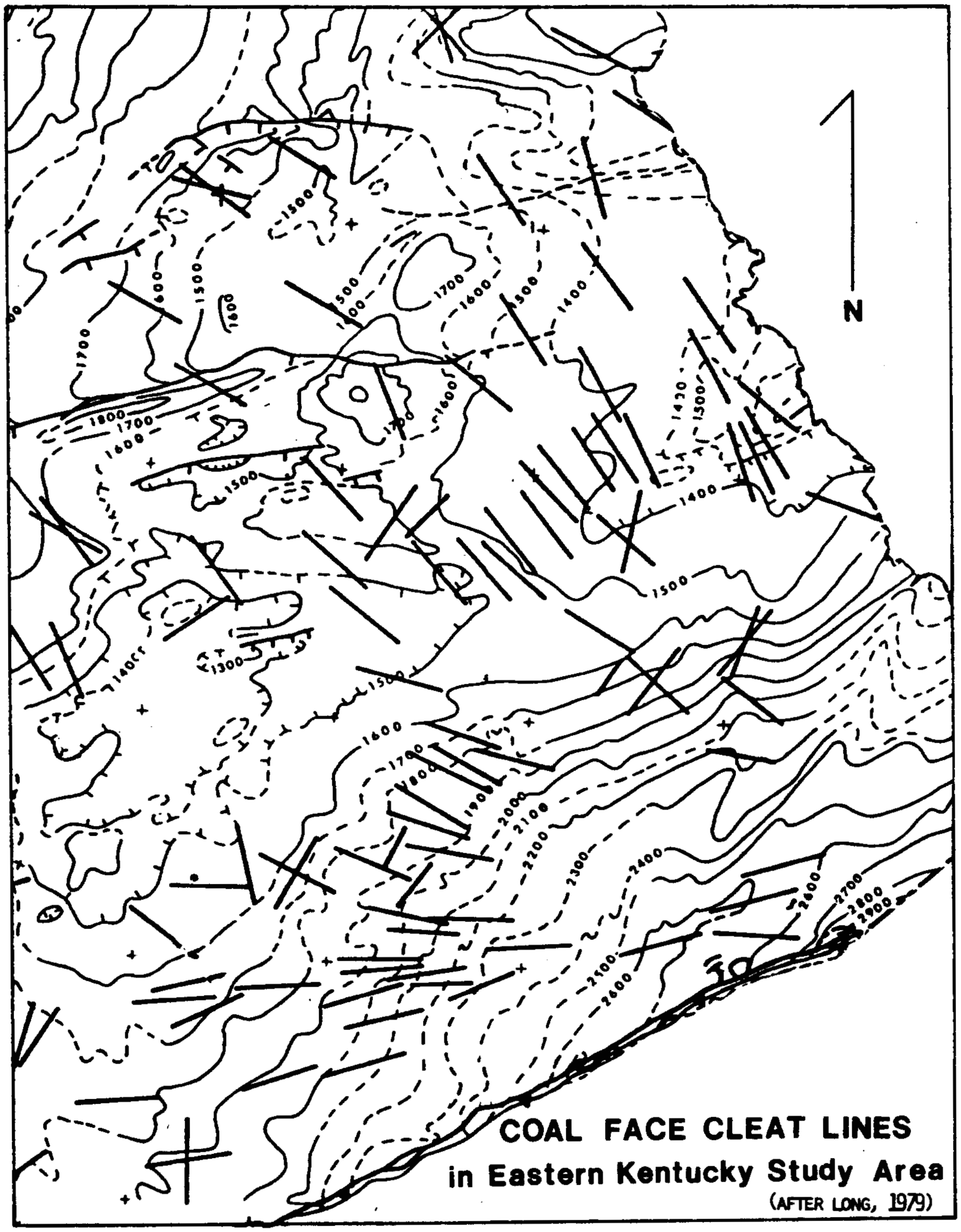


Figure 6. Coal face cleats (Long, 1979).

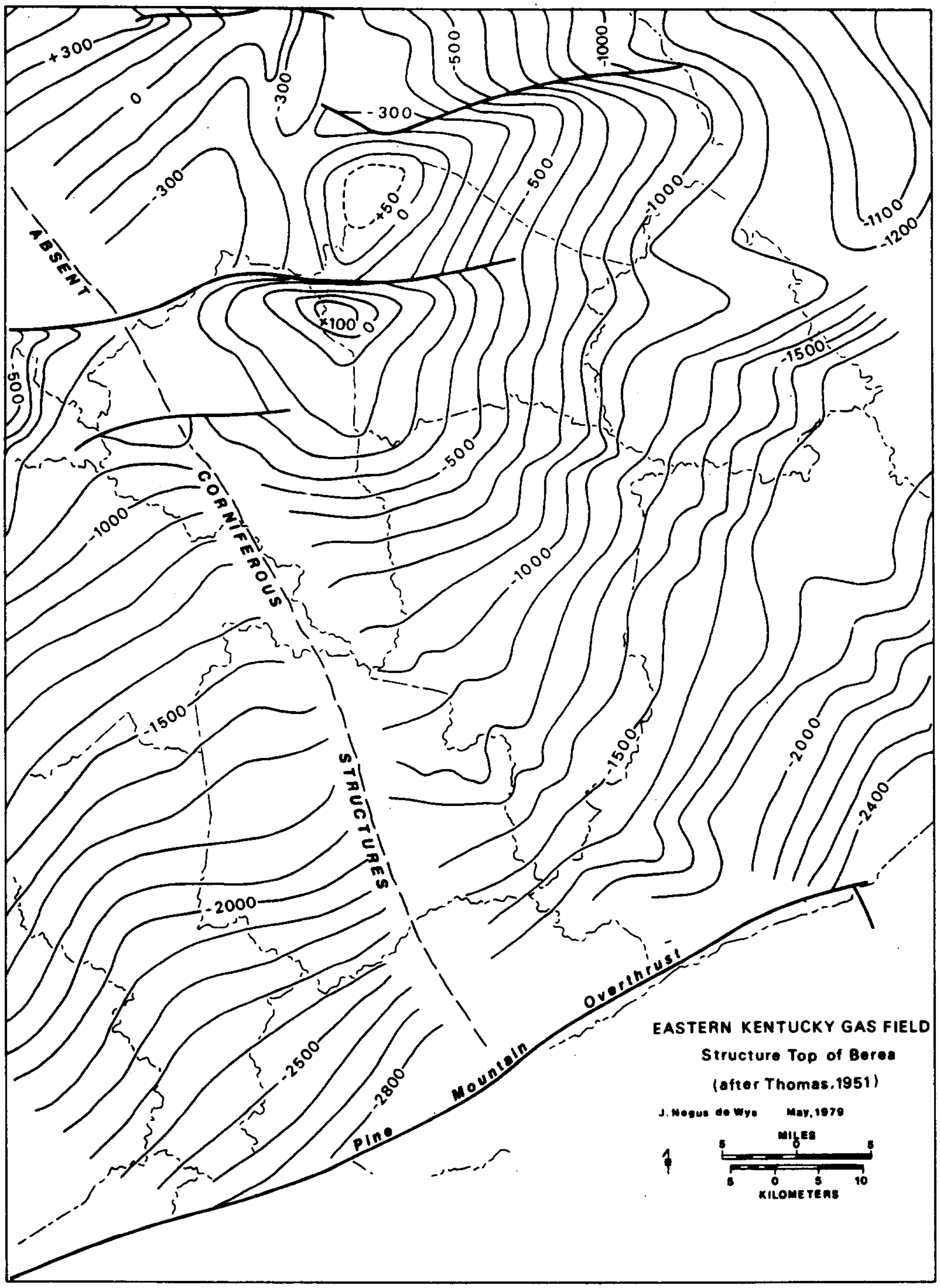


Figure 7. Structure on top of the Berea (after Thomas, 1951).

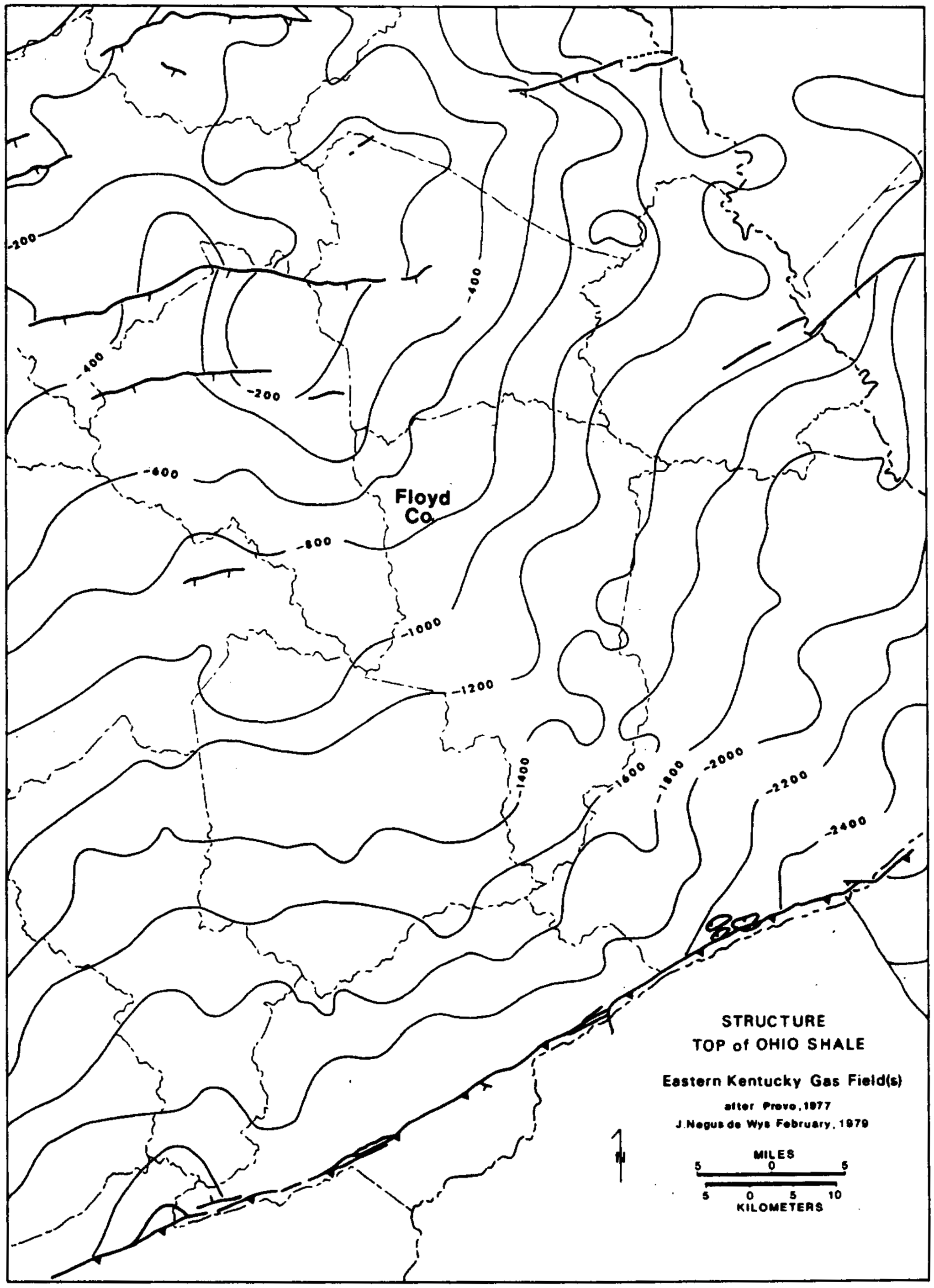


Figure 8. Structure on top of the Ohio Shale (after Provo, 1977).

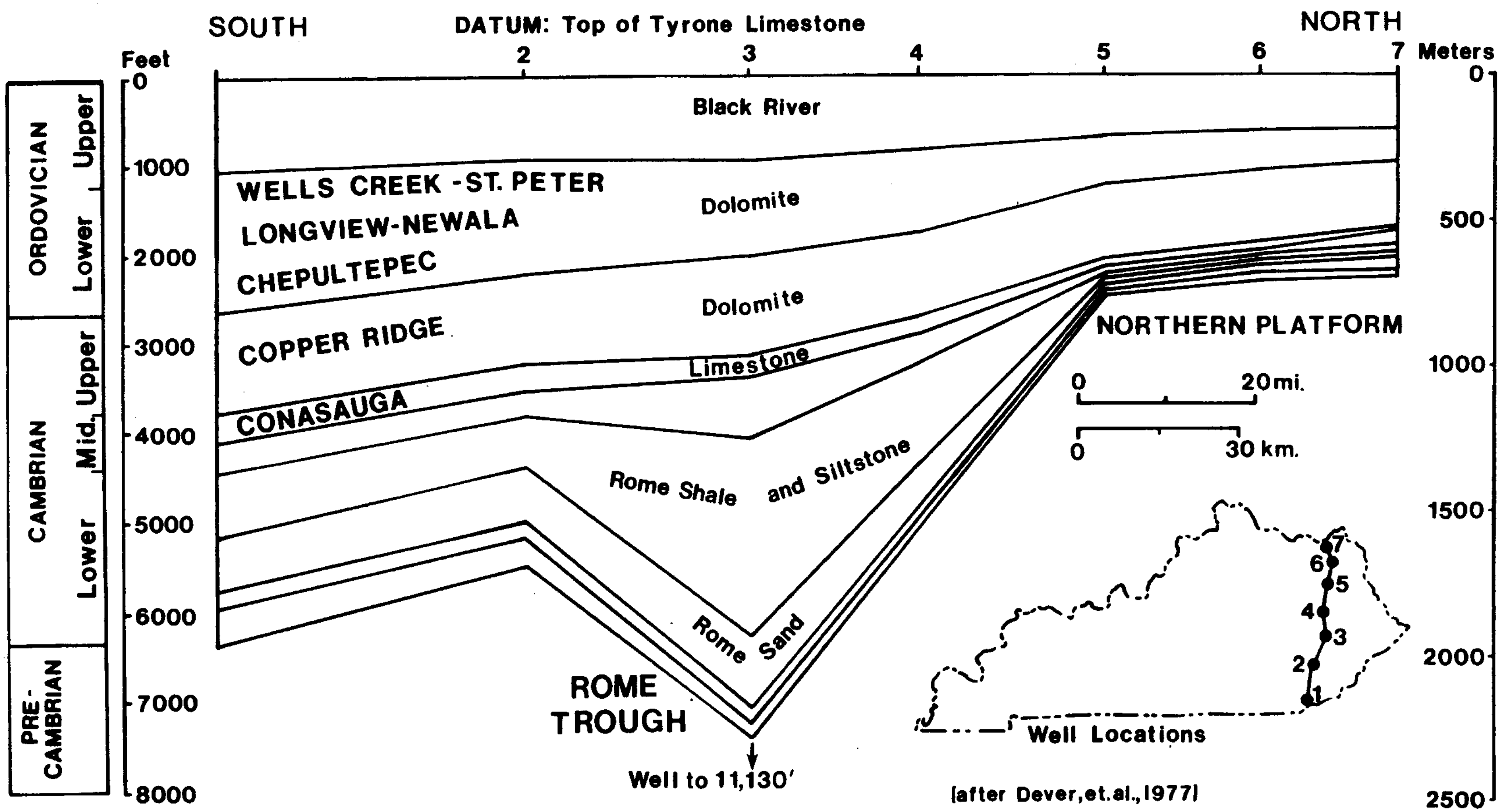


Figure 9. Evidence of major development of the Rome Trough in Cambrian time (after Dever, et al., 1977).

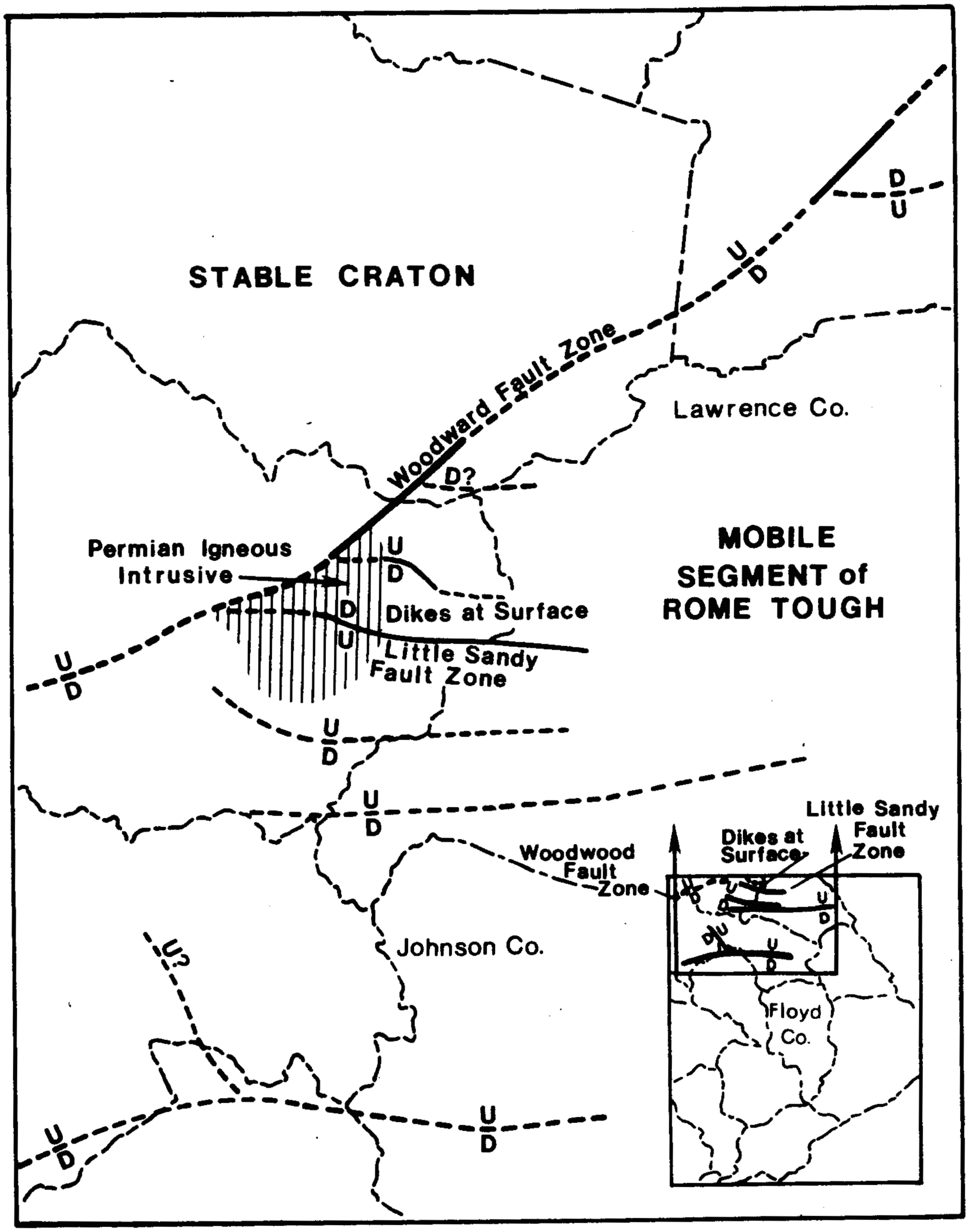


Figure 10. Location of Cambro-Ordovician growth faults trending east-to-west, Permian igneous intrusive, and Permian dikes at the surface, related to the Woodward Fault Zone. Position of map area is shown in relationship to study area in inset map (after Silberman, 1972).

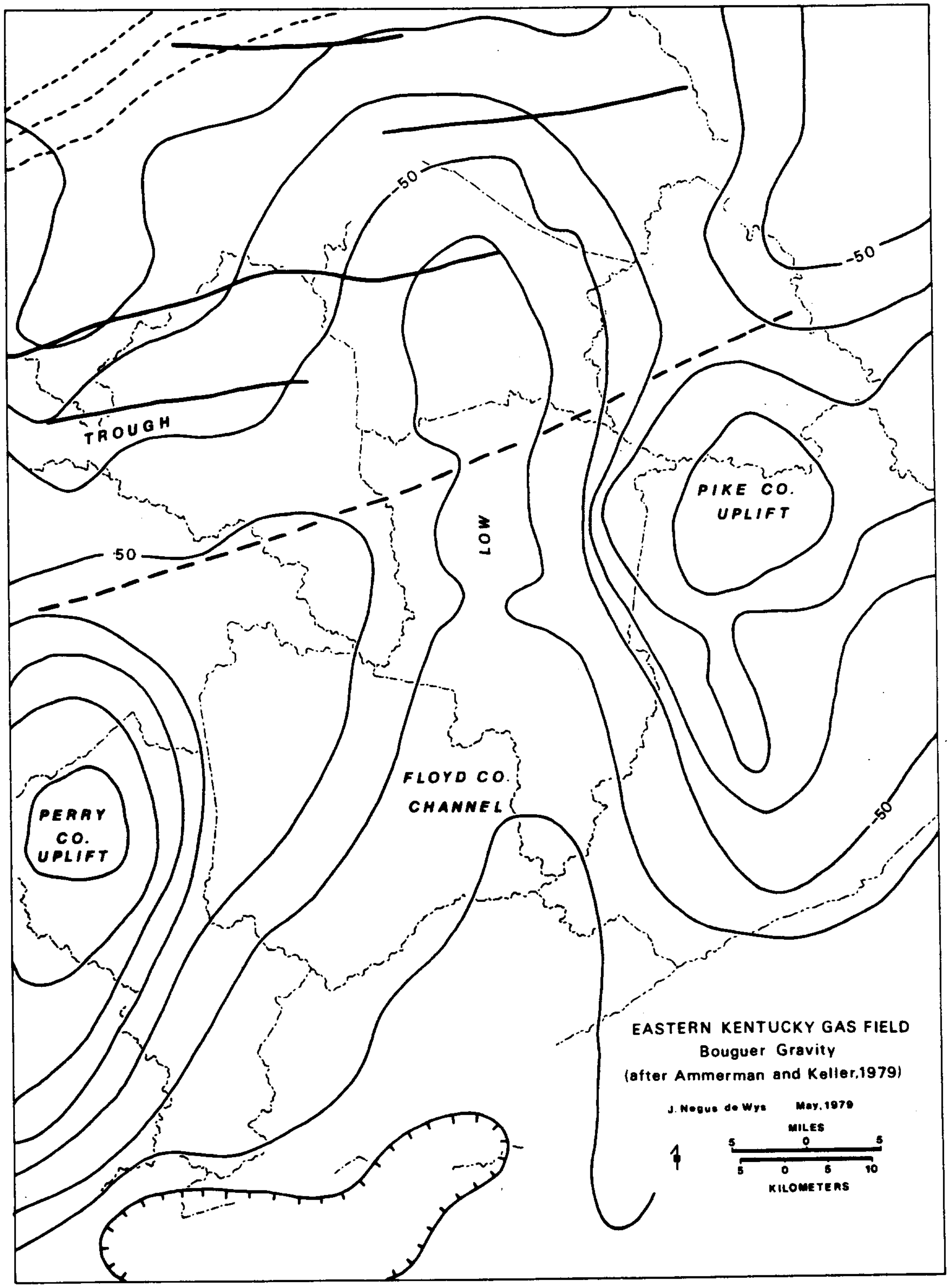


Figure 11. Bouguer gravity map with interpreted basement structures as named (after Ammerman and Keller, 1979). Surface faults and southern boundary of Rome Trough are indicated by solid line and heavy dashed line respectively.

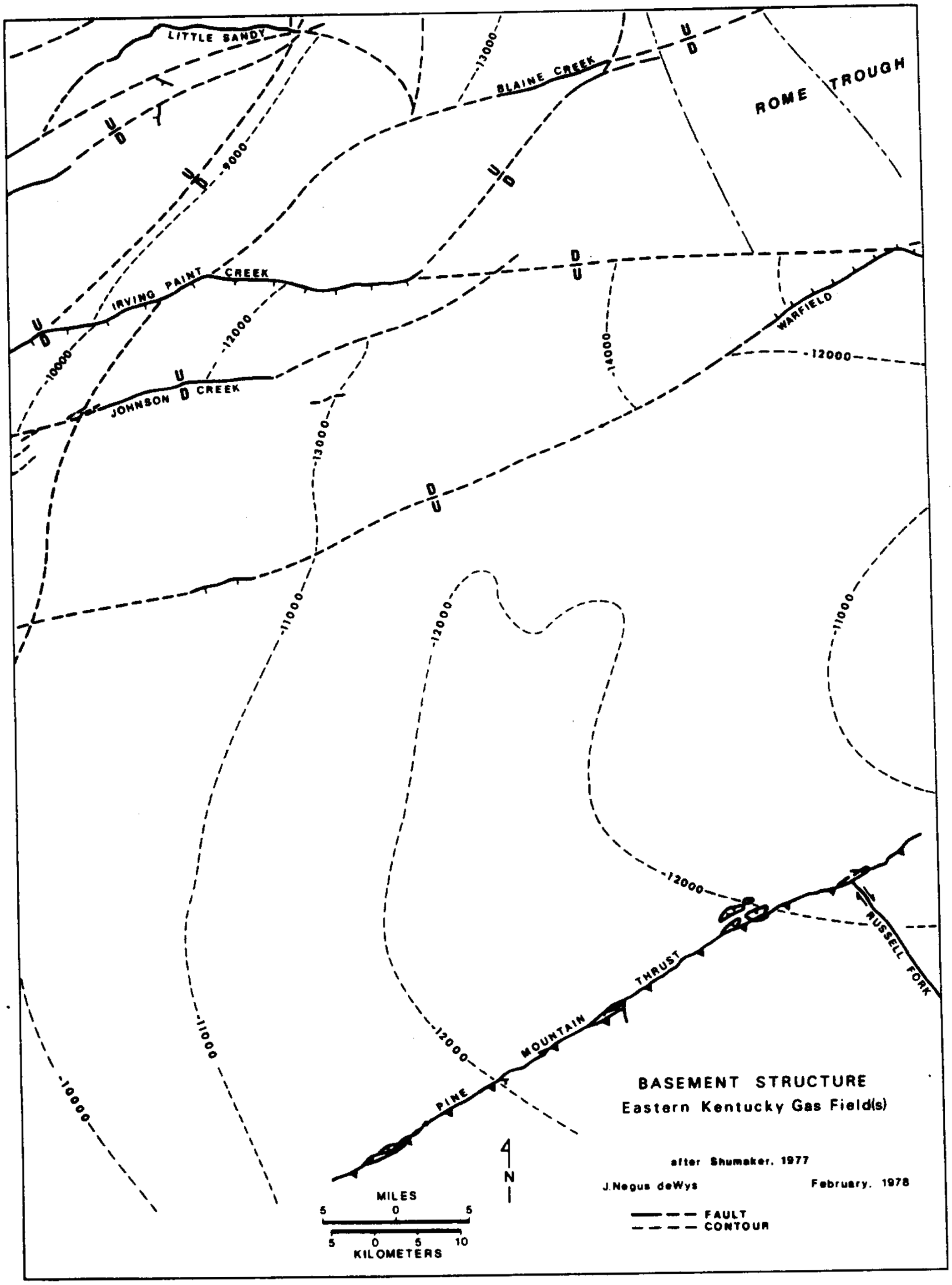


Figure 12. Basement structure (after Shumaker, 1977). Interpretation is based on gravity data.

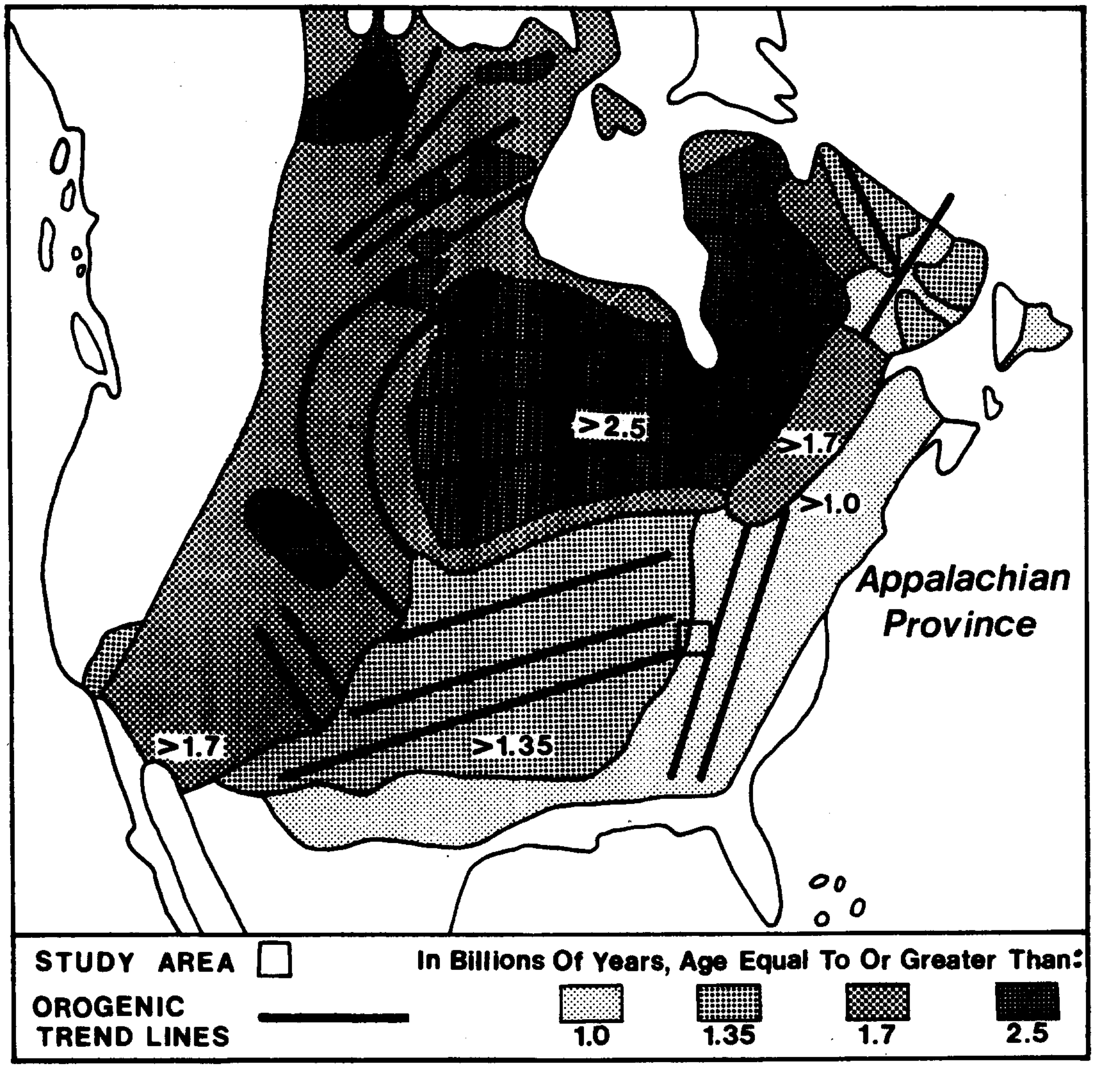


Figure 13. Geological provinces and orogenic trend lines (after Muehlberger, et al. 1967). The location of study area is shown by rectangle. Province ages are in billions of years.

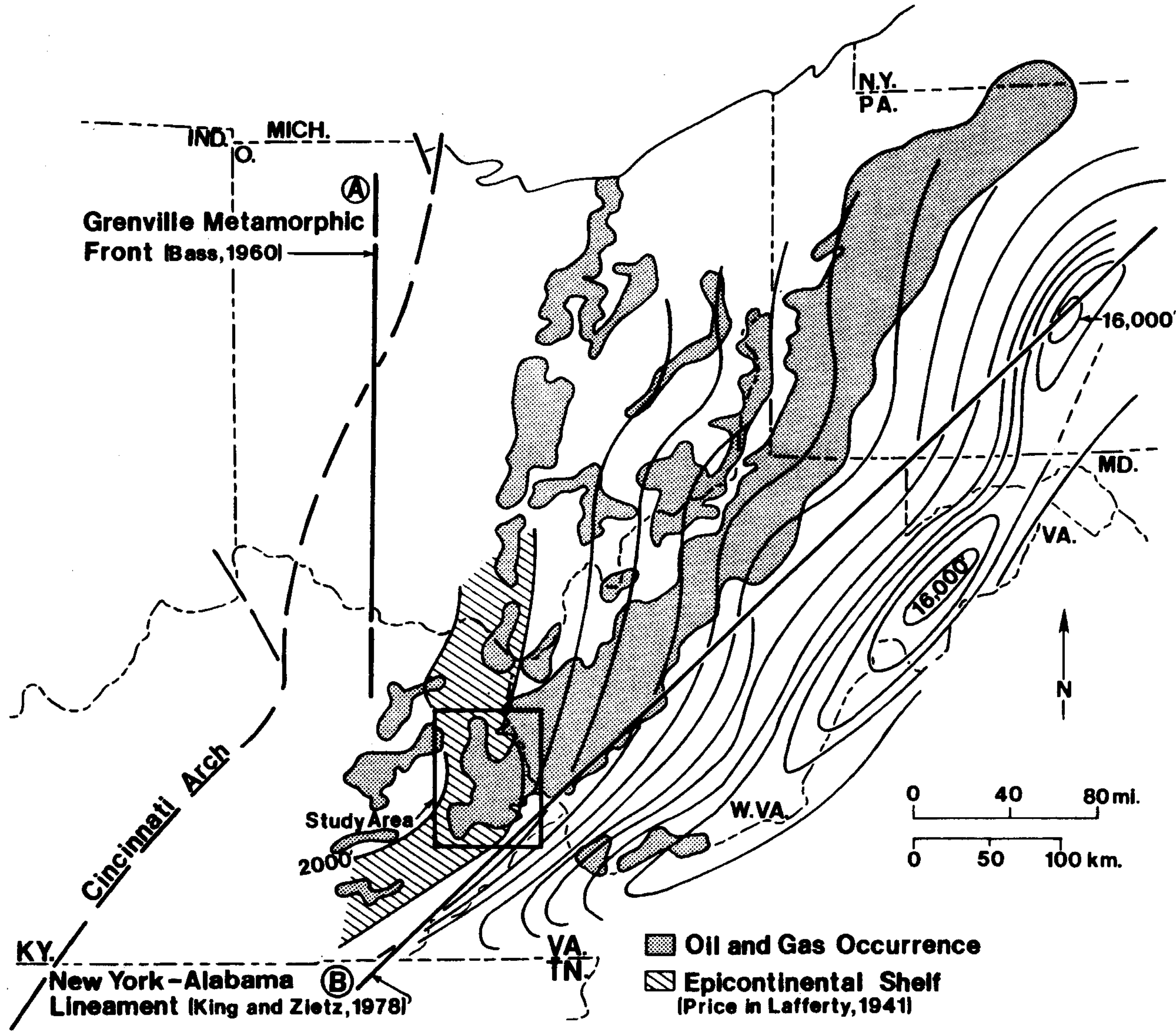


Figure 14. Field location relative to the epicontinental shelf (after Price in Lafferty, 1941), the New York-Alabama Lineament (King and Zietz, 1978), Grenville metamorphic front (Bass, 1960), Cincinnati Arch, and oil and gas occurrence. Contours are of thickness of early Paleozoic clastics.

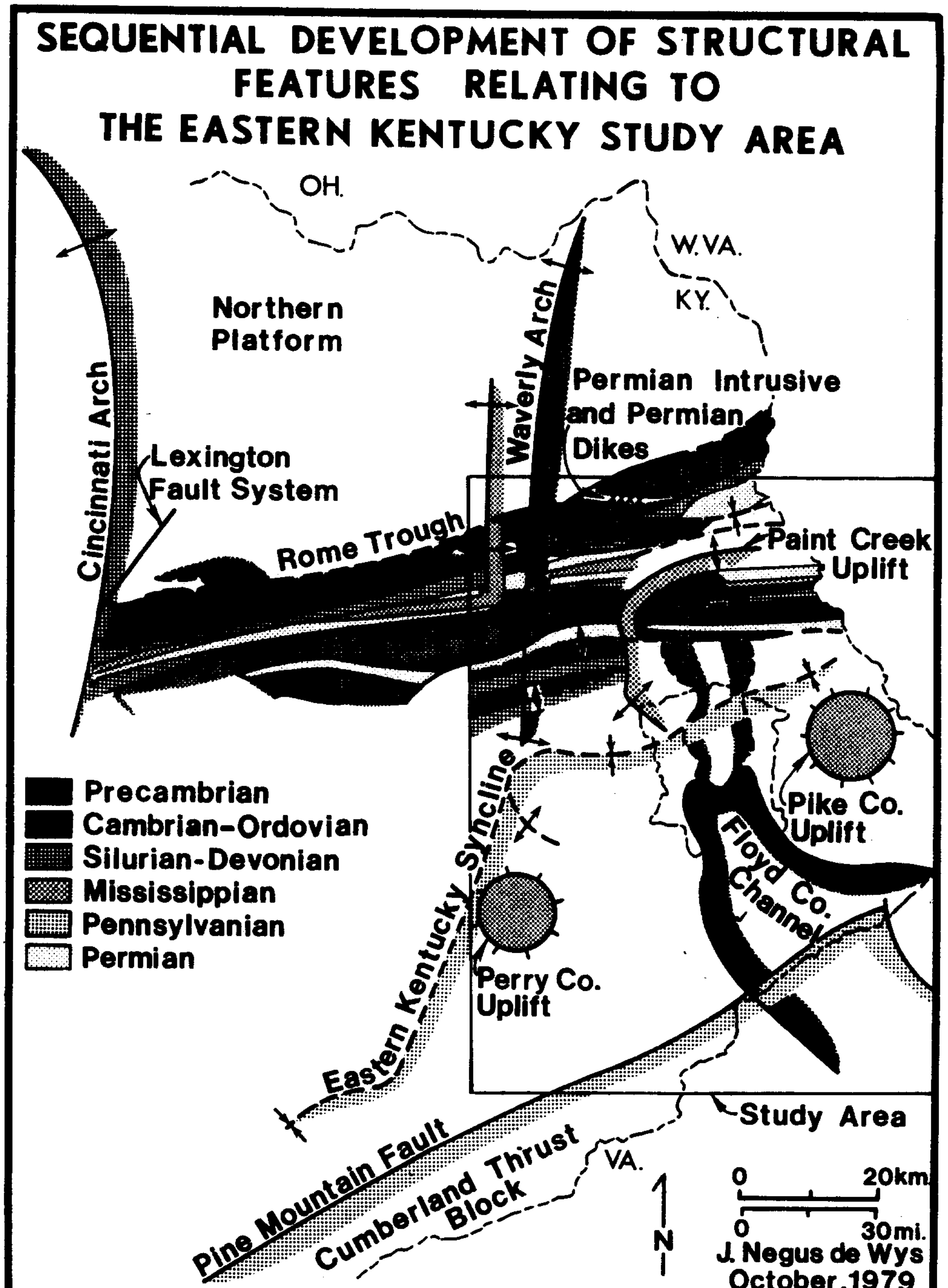


Figure 15. Sequential structural development.

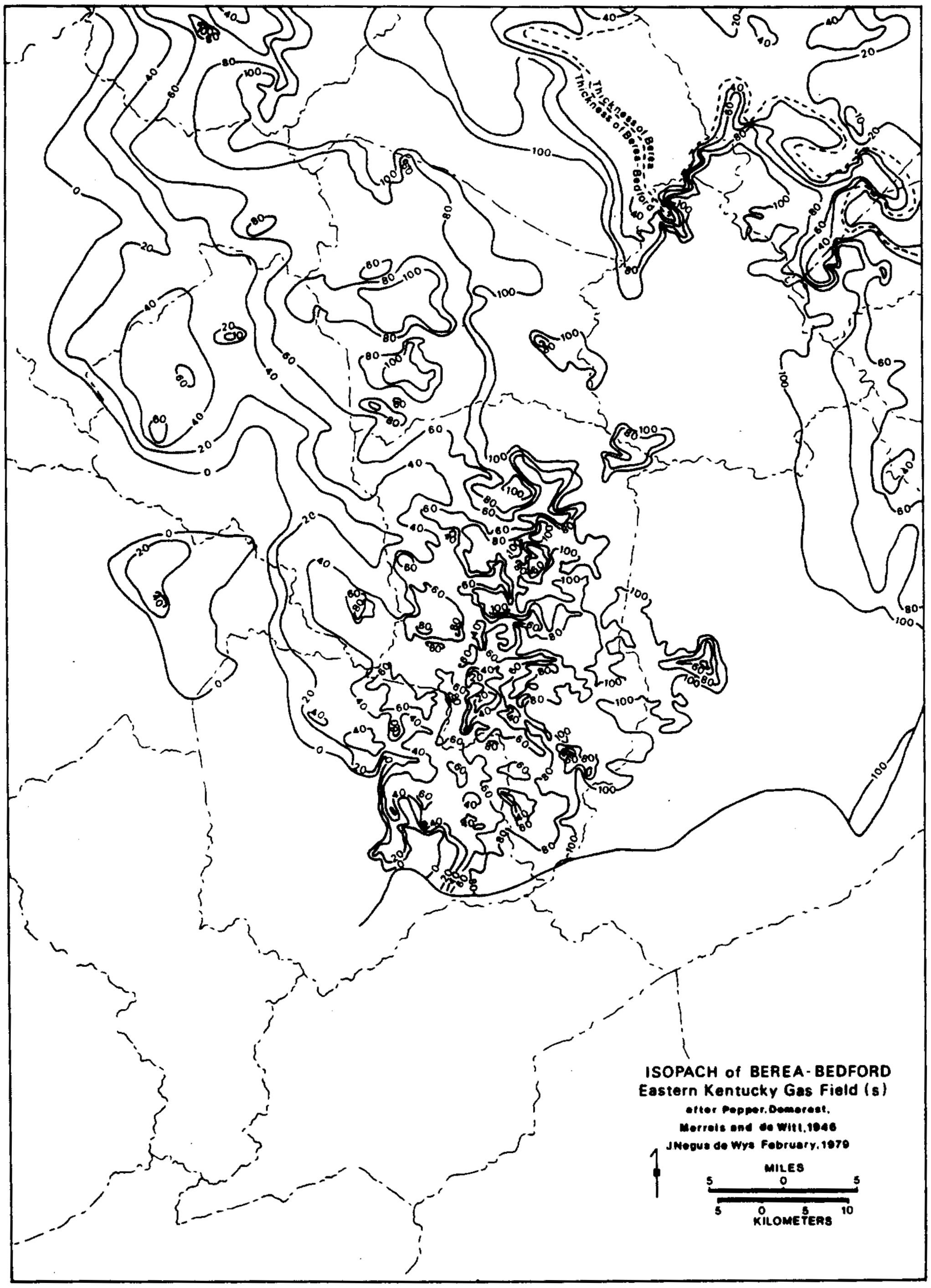


Figure 16. Isopach map of Berea-Bedford Sandstone (after Pepper, Demarest, Merrels, 2nd., and de Witt, Jr., 1946). At 0-isopach the unit becomes all shale. The >100-foot contour area runs almost N-S adjacent to the eastern side of the highest production area in Floyd County.

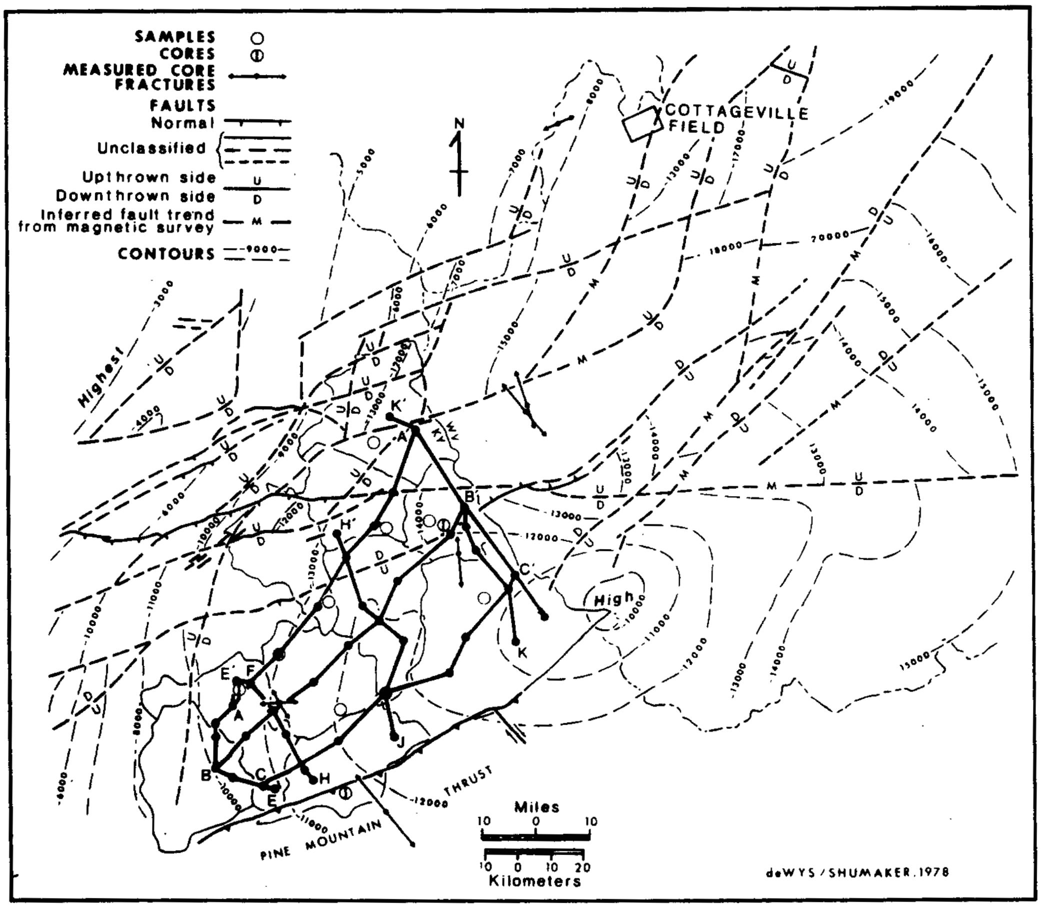
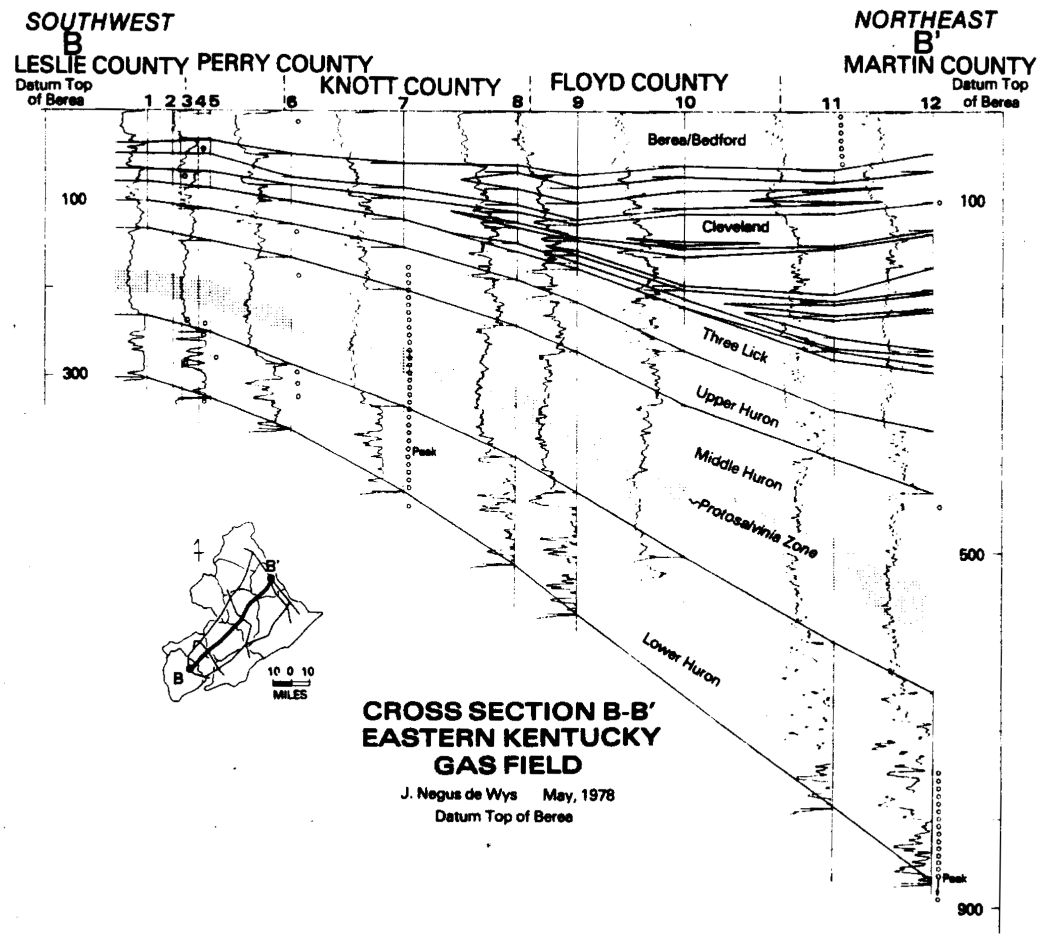


Figure 17. The locations of cross sections constructed from formation density logs. Basement structure (after Shumaker, 1978) is shown in dashed lines.



<u>Figure 18.</u> Stratigraphic cross section B-B', southwest to northeast through the field center, showing log traces of natural radioactivity from the formation density logs. Intertonguing of the black and gray shales in the Cleveland are usually related to the changes in natural radioactivity. The black shale in the Cleveland is shaded gray.

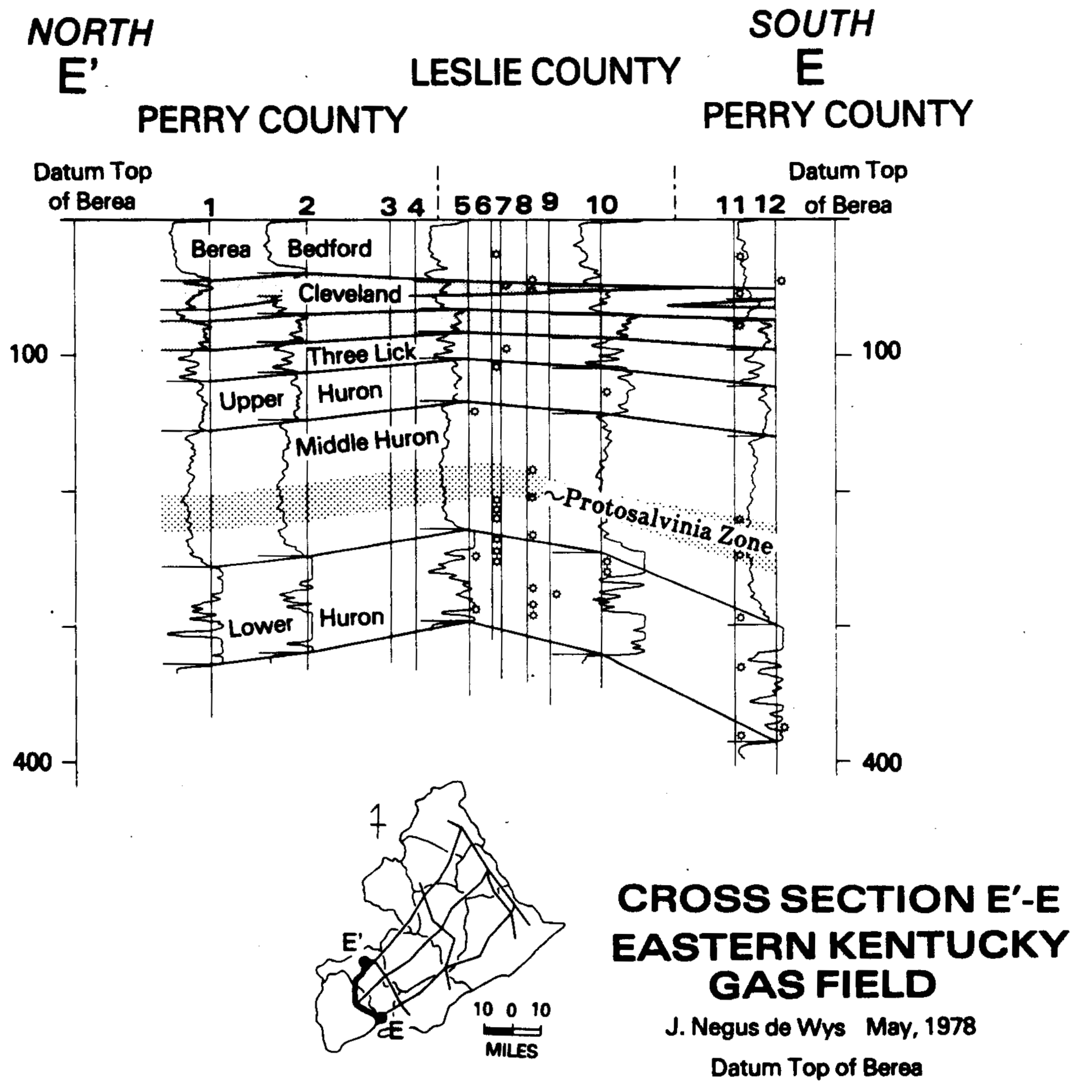


Figure 19. Stratigraphic cross section E'-E, north to south through the southern end of the field, showing log traces of natural radioactivity from the gamma ray logs. The black shale in the Cleveland is shaded gray.

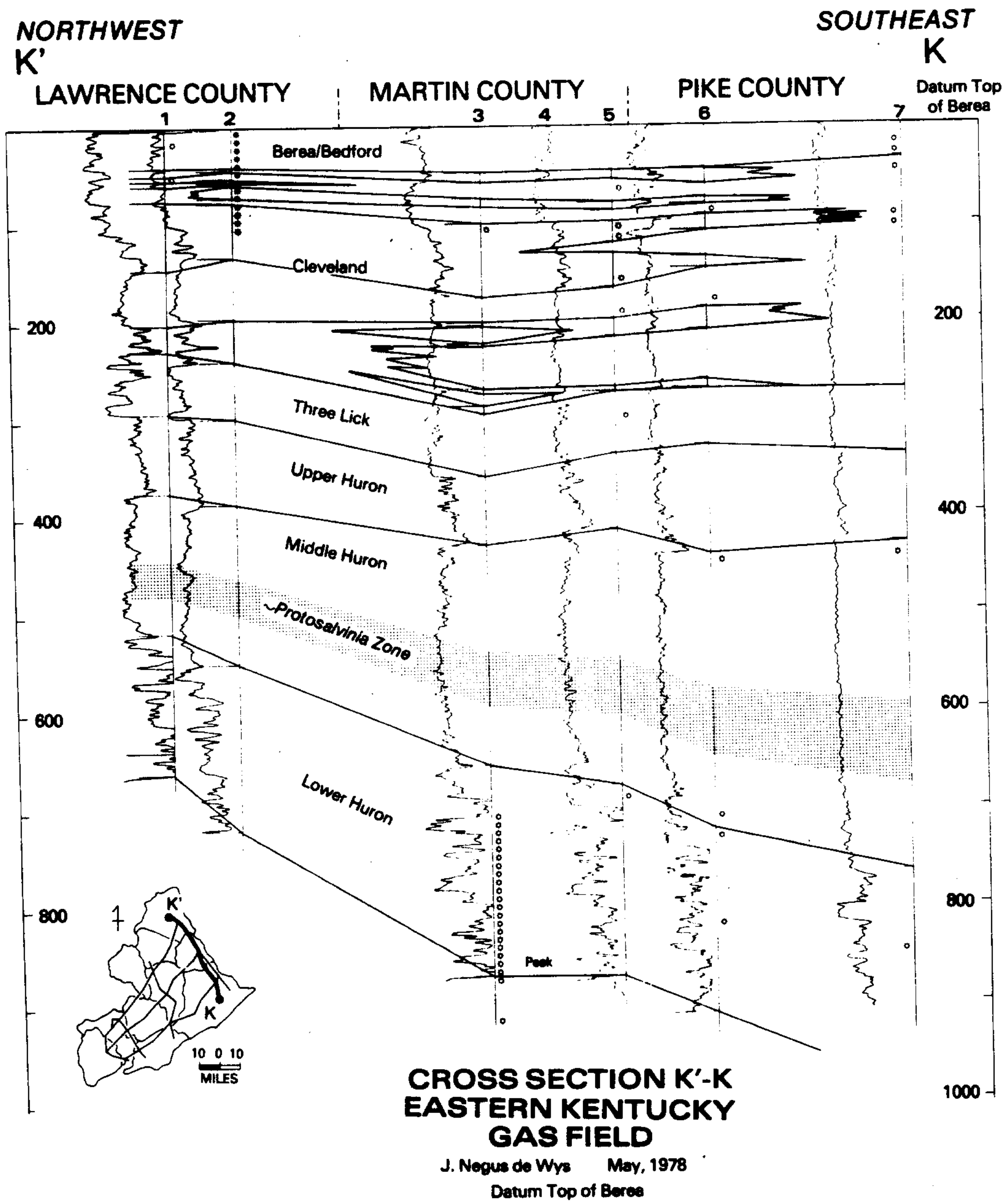


Figure 20. Stratigraphic cross section K'-K, north to south through the northern end of the field, showing traces of natural radioactivity from the gamma ray logs. The Protosalvinia zone is where the brown algae occur most commonly. It has been reported at horizons in the Three Lick down through the Lower Huron (Provo, 1977; Swager, 1978).

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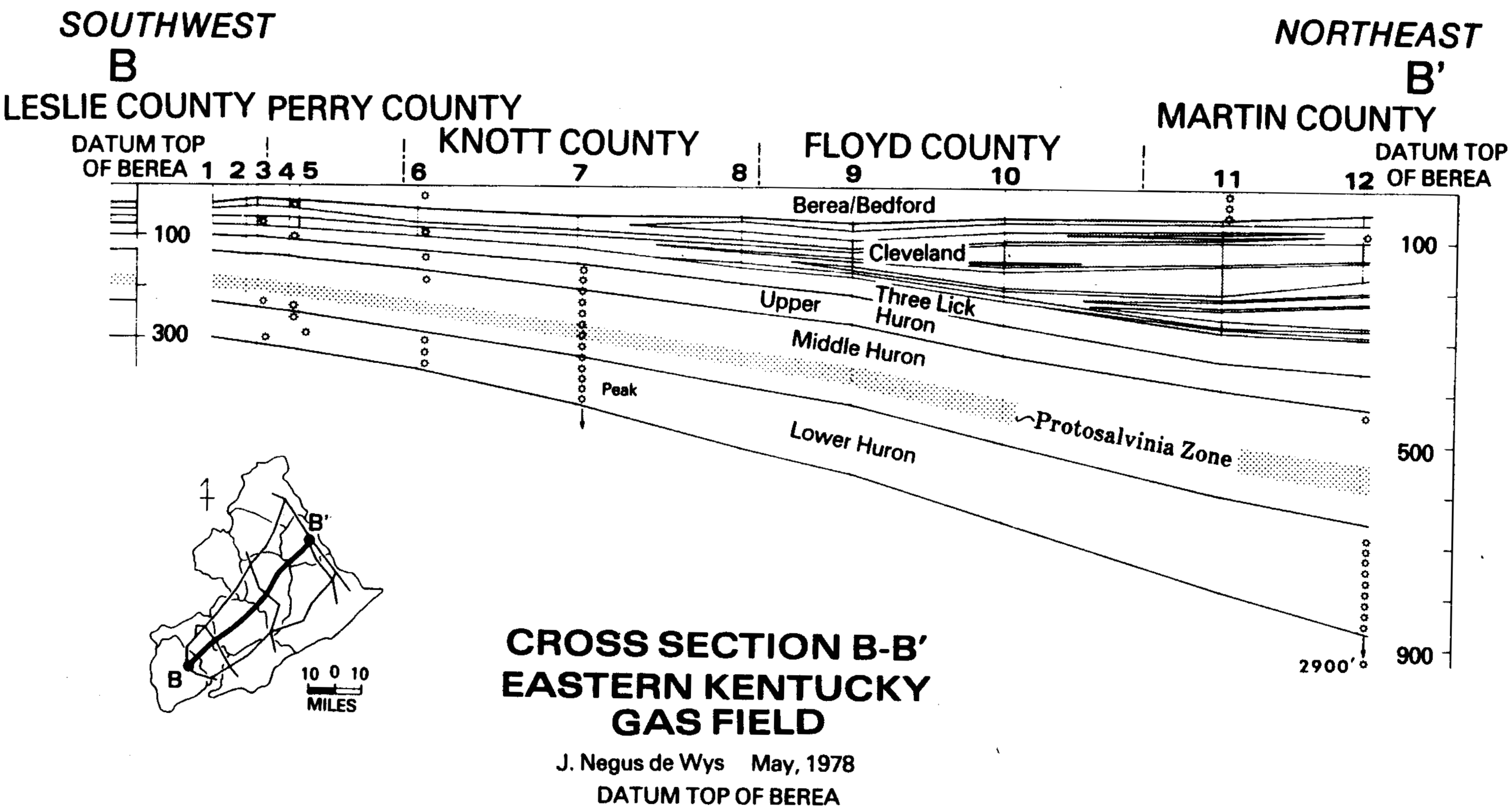

Figure 21. Stratigraphic cross section B-B'; datum: top of Berea. The intertonguing black and gray shales in the Cleveland, especially over the center of the field, are apparent in this cross section. Where temperature logs are available, gas occurrence is noted.

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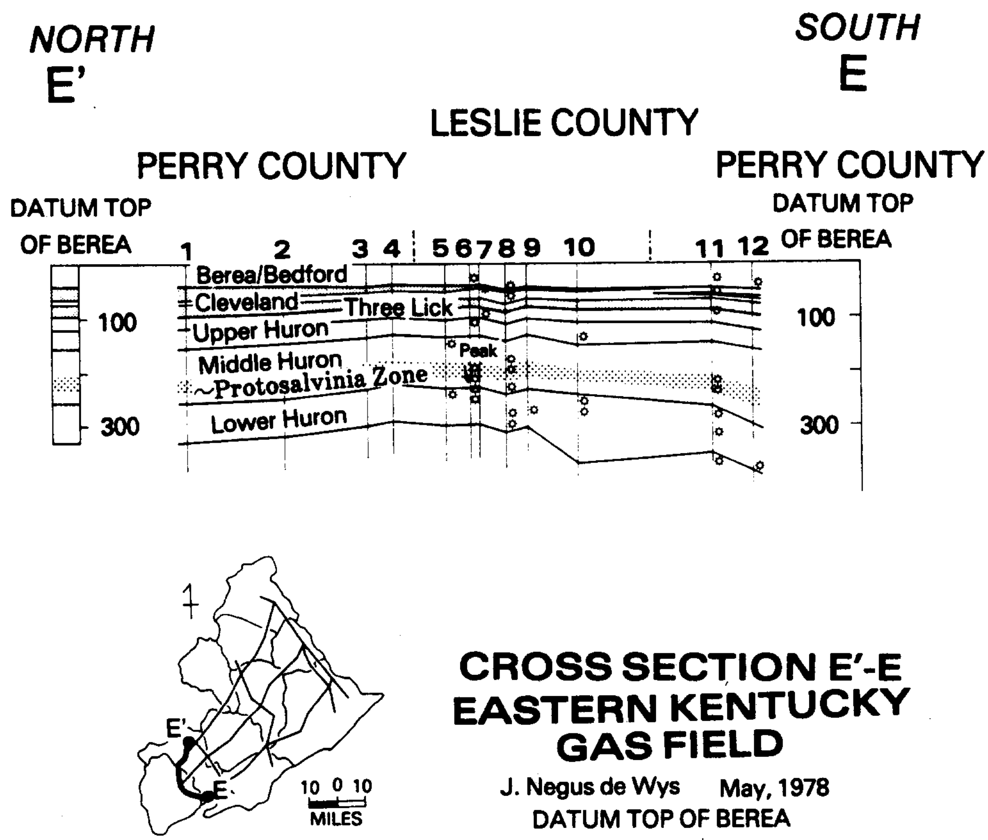

Figure 22. Stratigraphic cross section E'-E; datum: top of Berea. Slight structure at the base of the section is apparent. Gas occurrence from temperature logs is noted, where temperature logs are available.

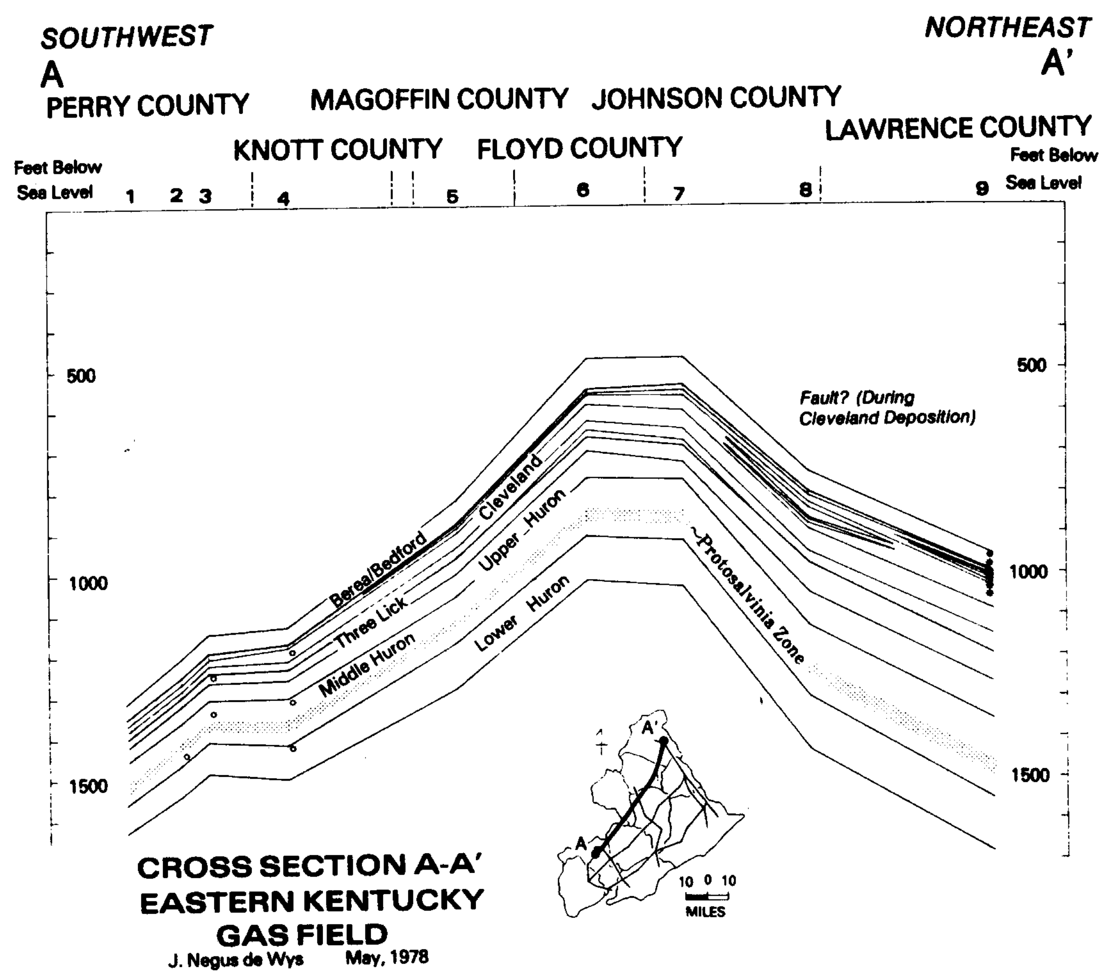

Figure 23. Structural-stratigraphic cross section A-A'. Oil and gas occurrence from temperature logs and drilling records is noted.

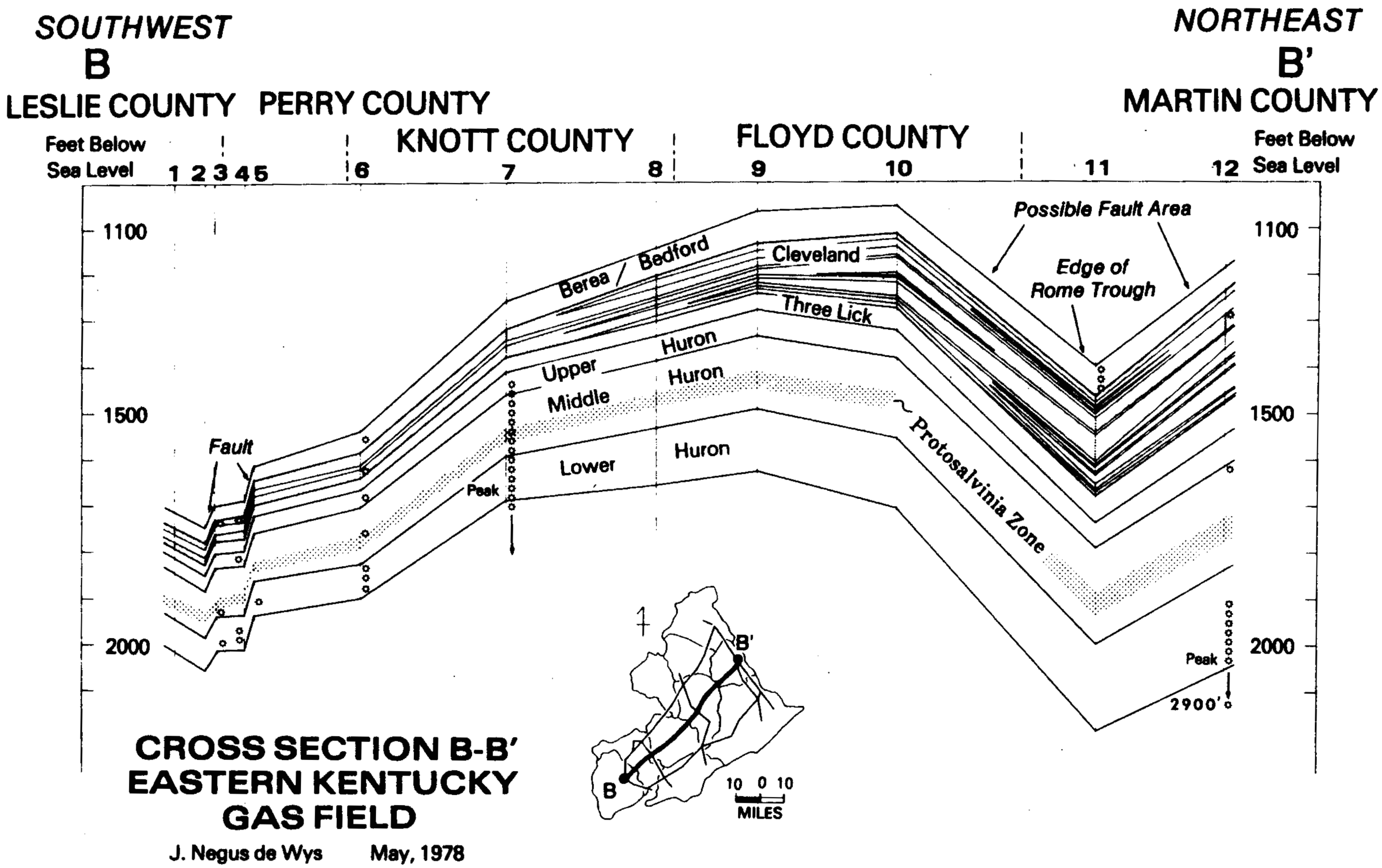

Figure 24. Structural-stratigraphic cross section B-B'. Gas occurrence is noted where temperature logs or drilling records are available.

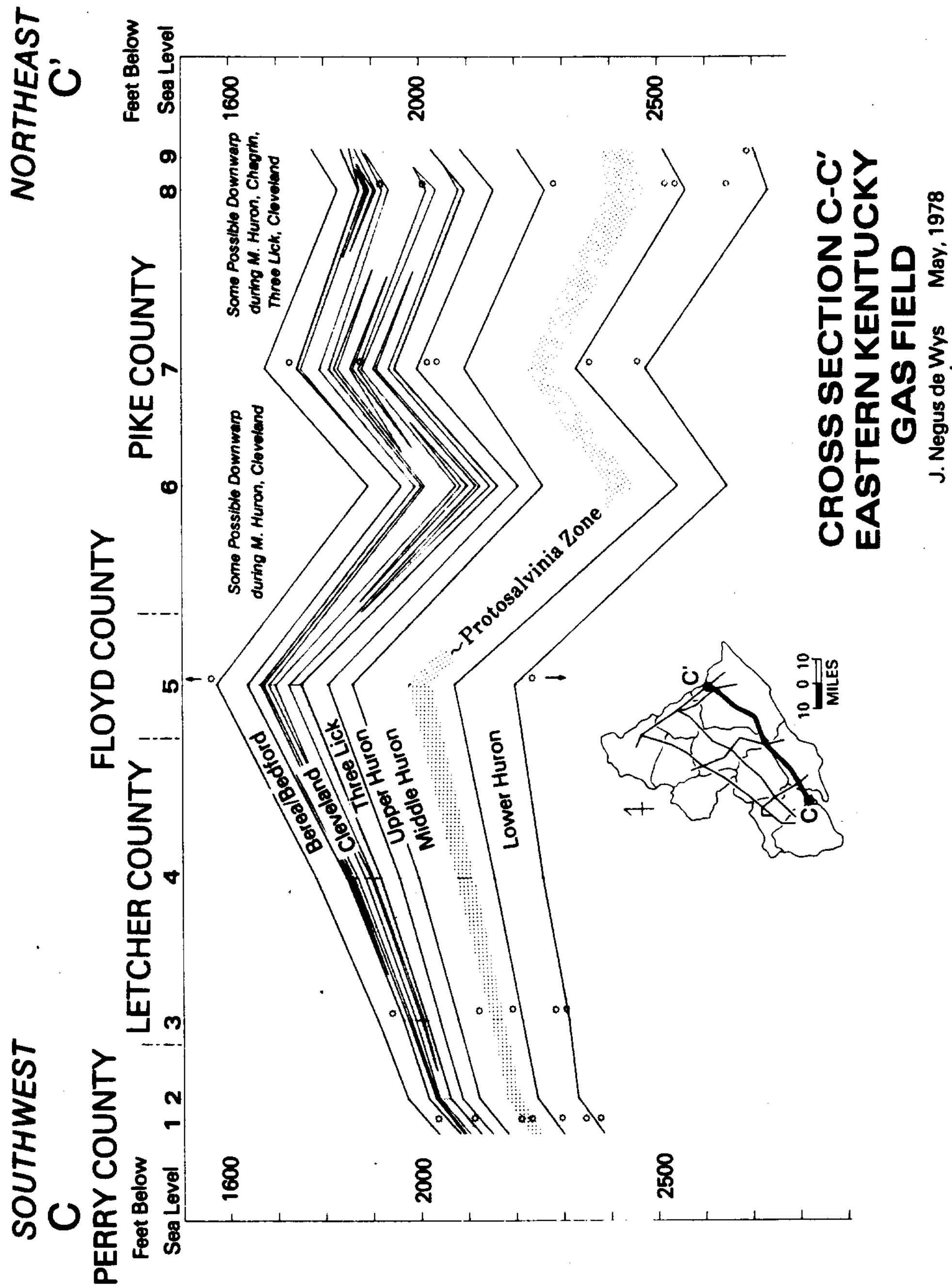

Figure 25. Structural-stratigraphic cross section C-C'. Gas occurrence is noted where temperature logs are available.

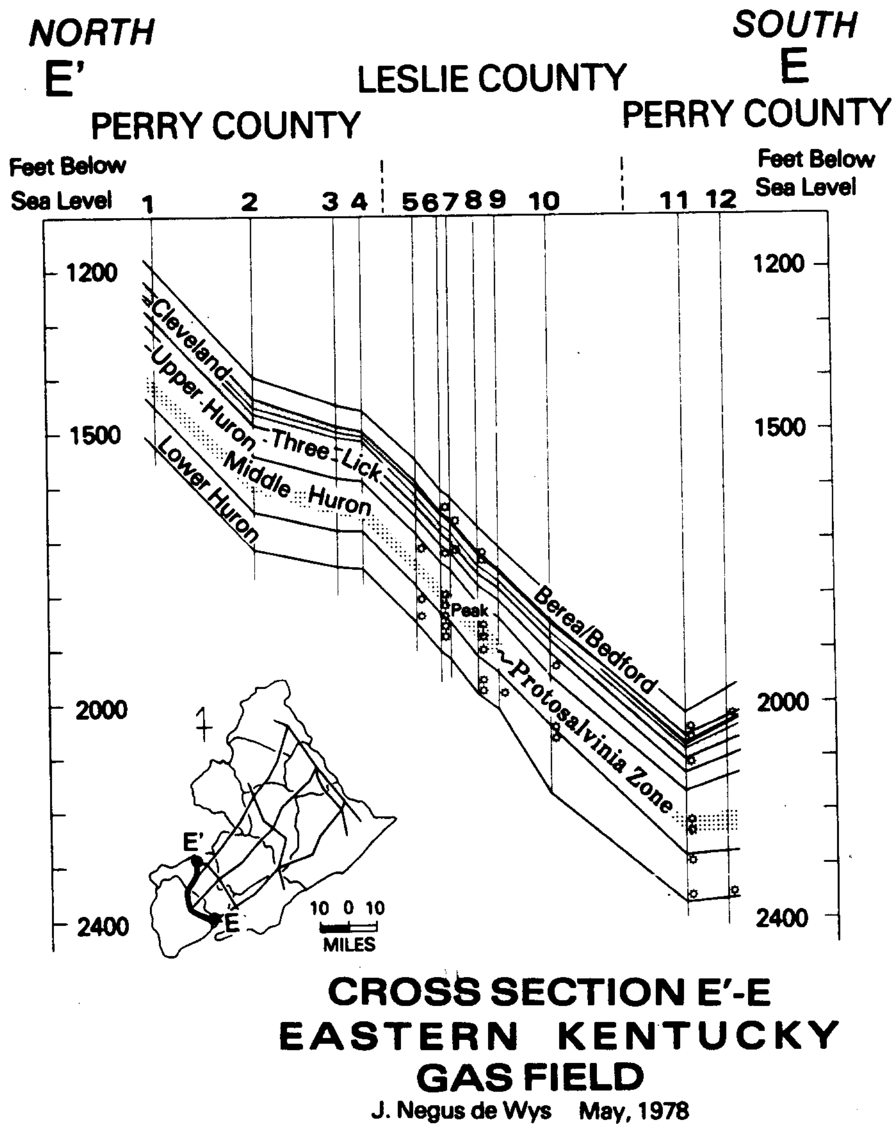

Figure 26. Structural-stratigraphic cross section E-E'. Gas occurrence is noted where temperature logs are available.

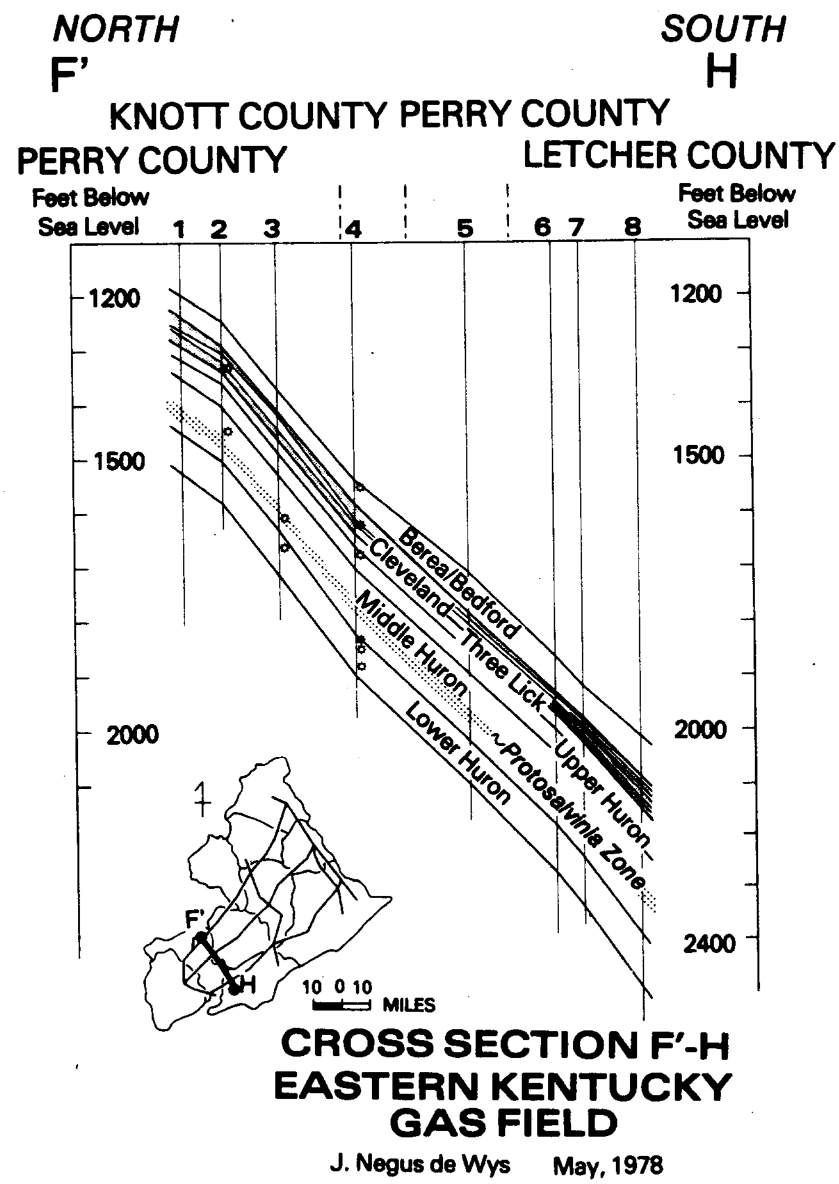

Figure 27. Structural-stratigraphic cross section F'-H. Gas occurrence is noted where temperature logs are available.

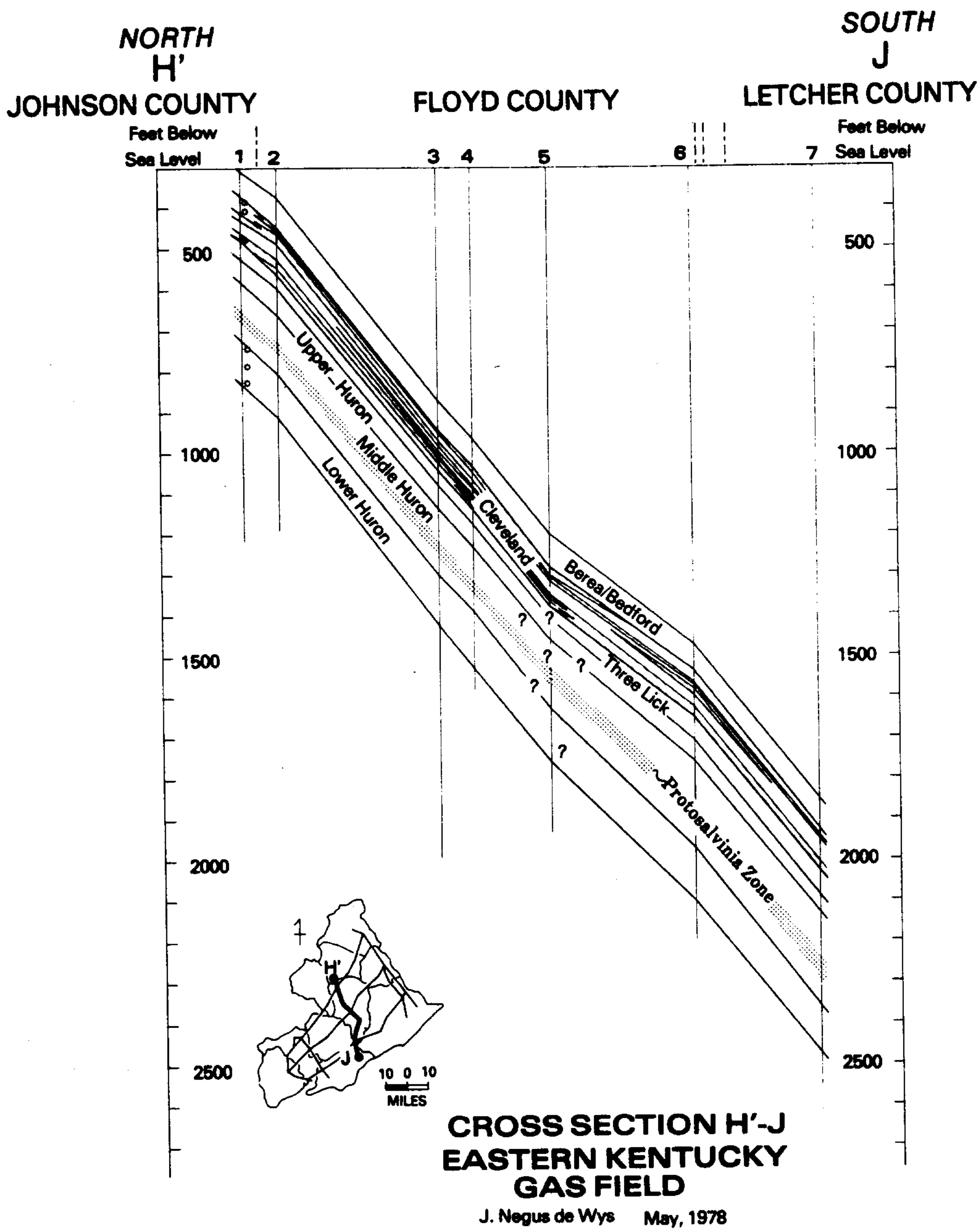

Figure 28. Structural-stratigraphic cross section H'-J. Gas occurrences are noted where temperature logs are available.

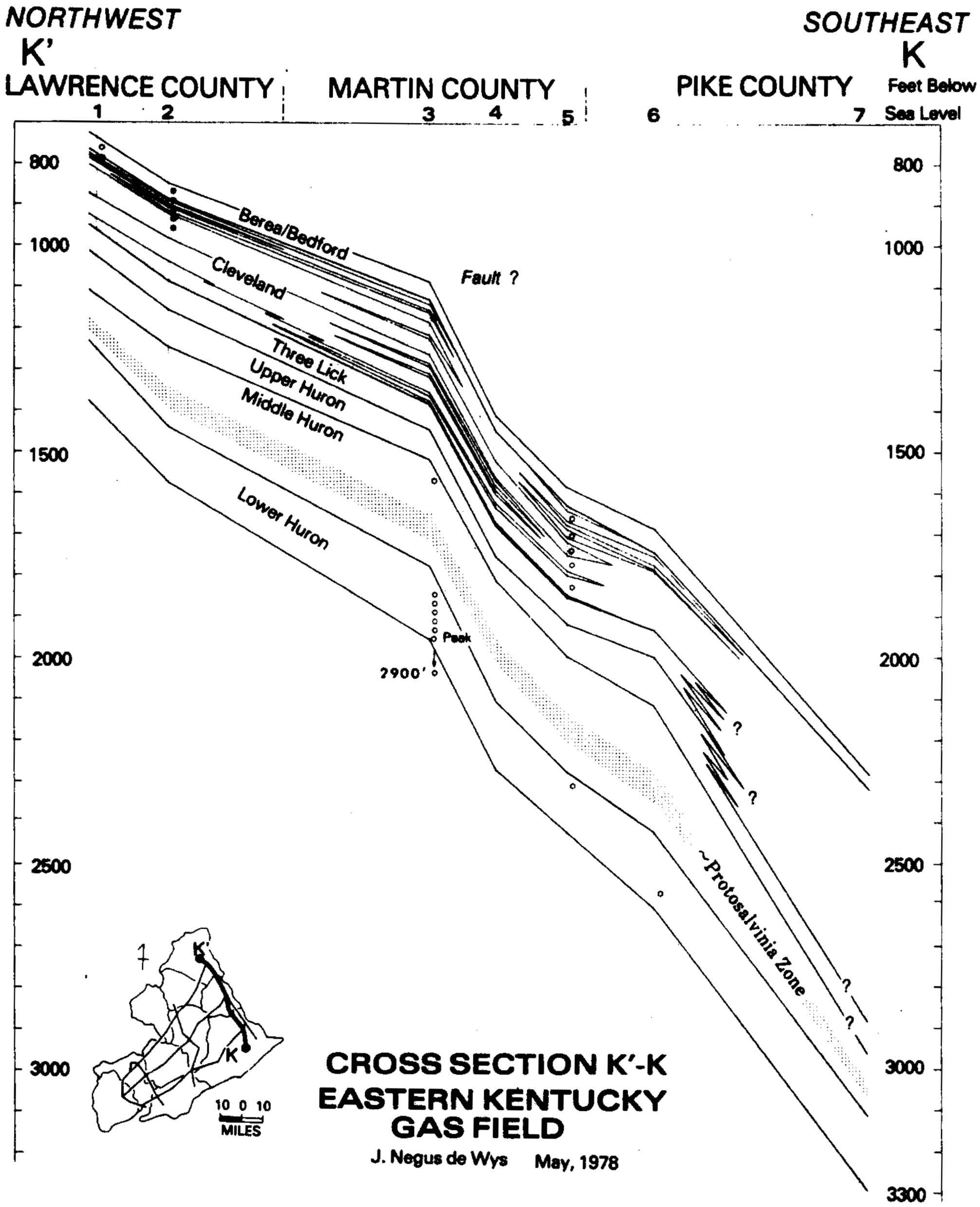

Figure 29. Structural-stratigraphic cross section K'-K. Gas occurrence is noted where temperature logs are available.

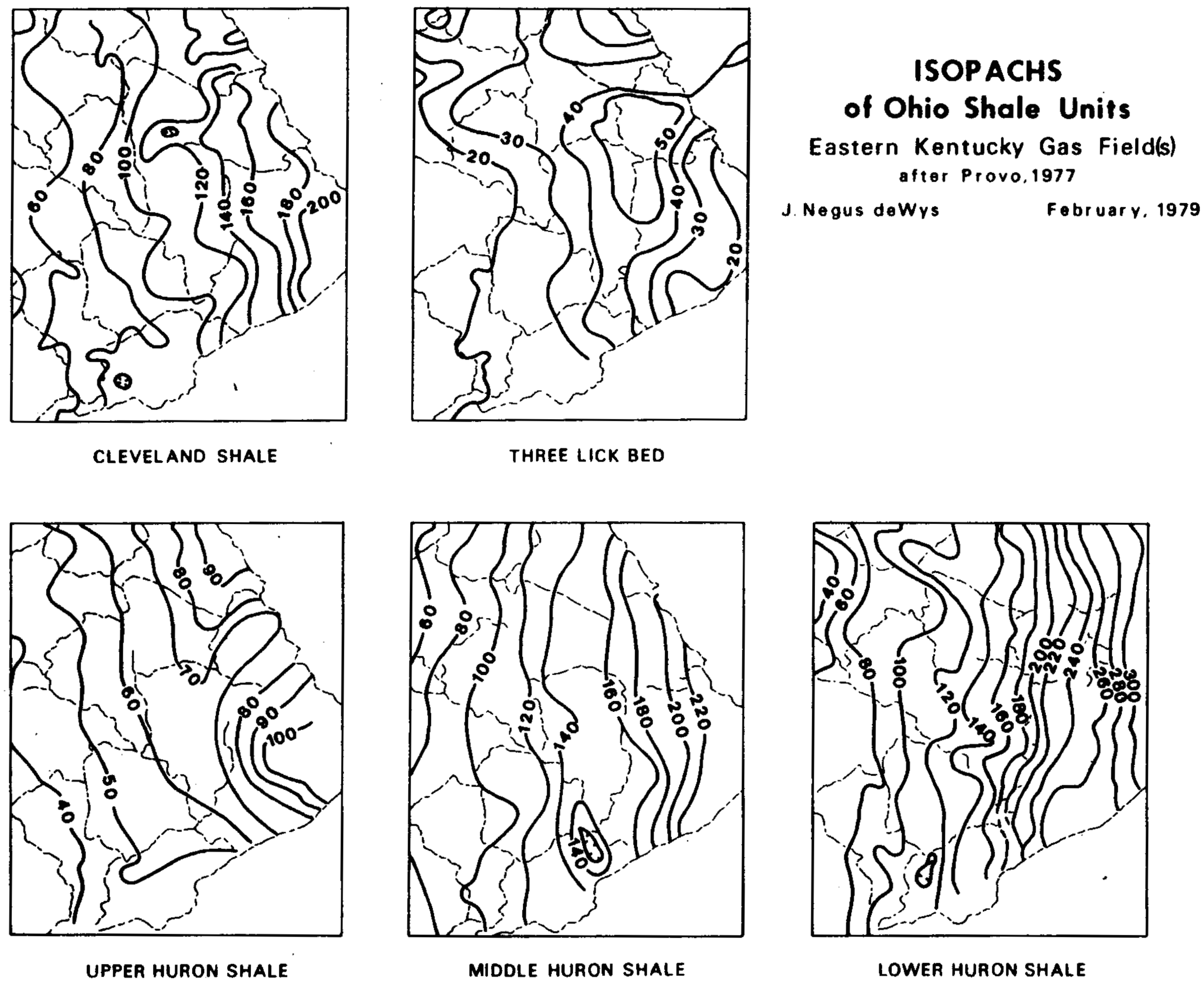

Figure 30. Isopach maps of the Cleveland, Three Lick, Upper Huron, Middle Huron, and Lower Huron units (after Provo, 1977). About 250 wireline logs and drillers' logs were used in the preparation of these maps. Note changing strike of isopachs with progression up the section. The thickness of units W-E also changes up the section, suggesting changes in the rate of basinal subsidence.

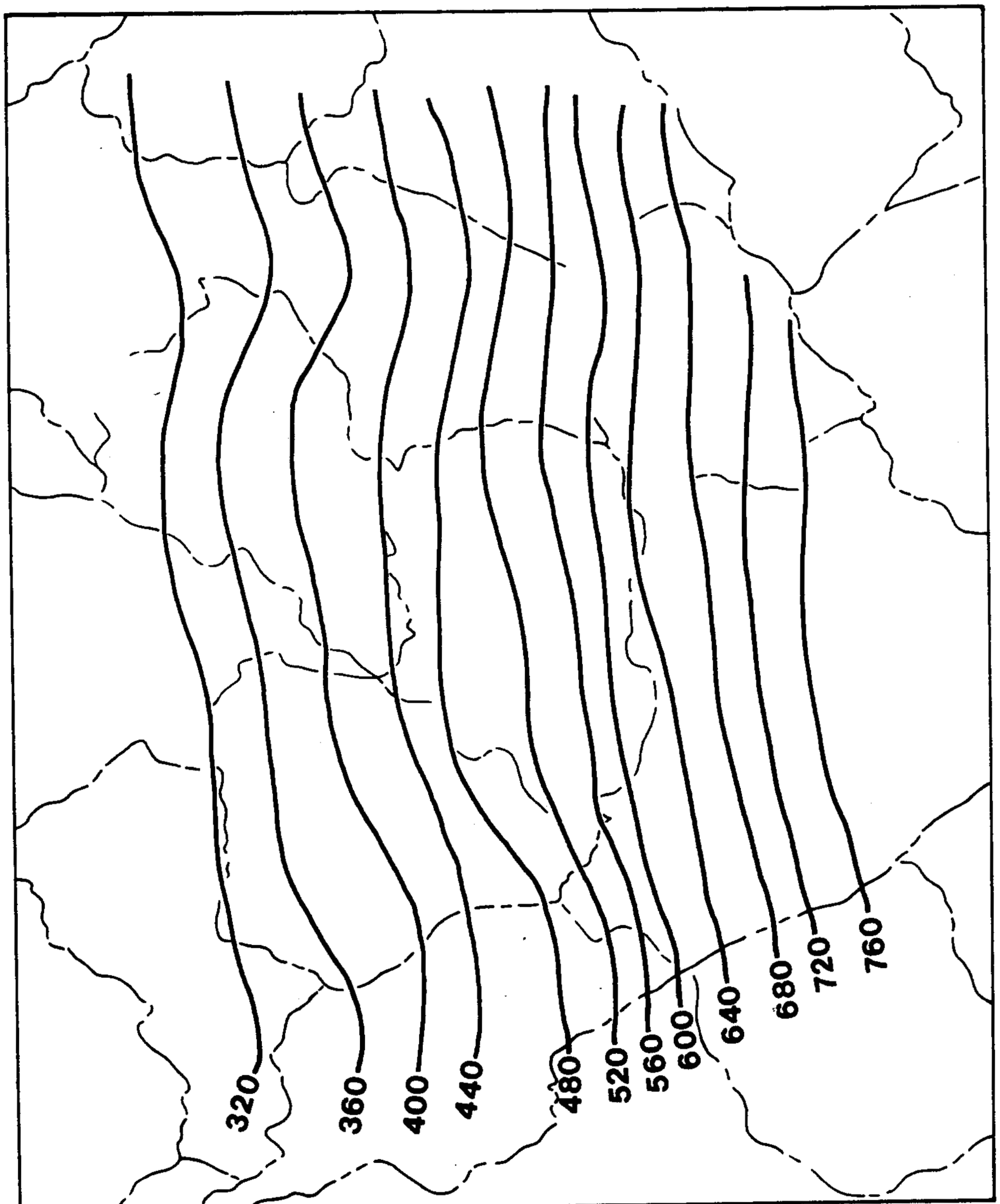

Figure 31. Isopach map of total Ohio Shale.

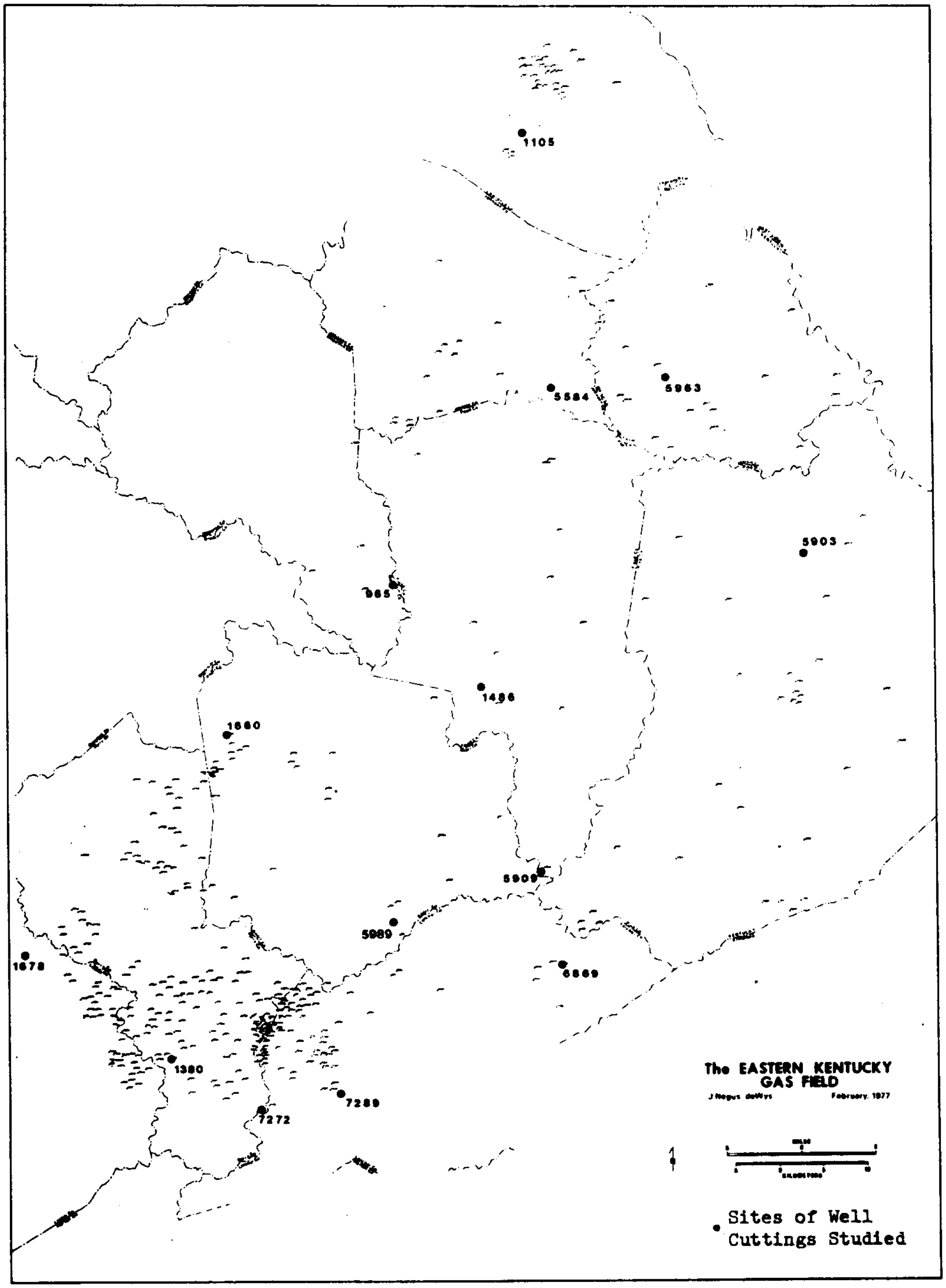

Figure 32. Location of wells from which cuttings are studied (large dots). Well #1660 is studied by geochemistry only. Small numbers are locations from which gamma ray logs are available, but not always usable for this study.

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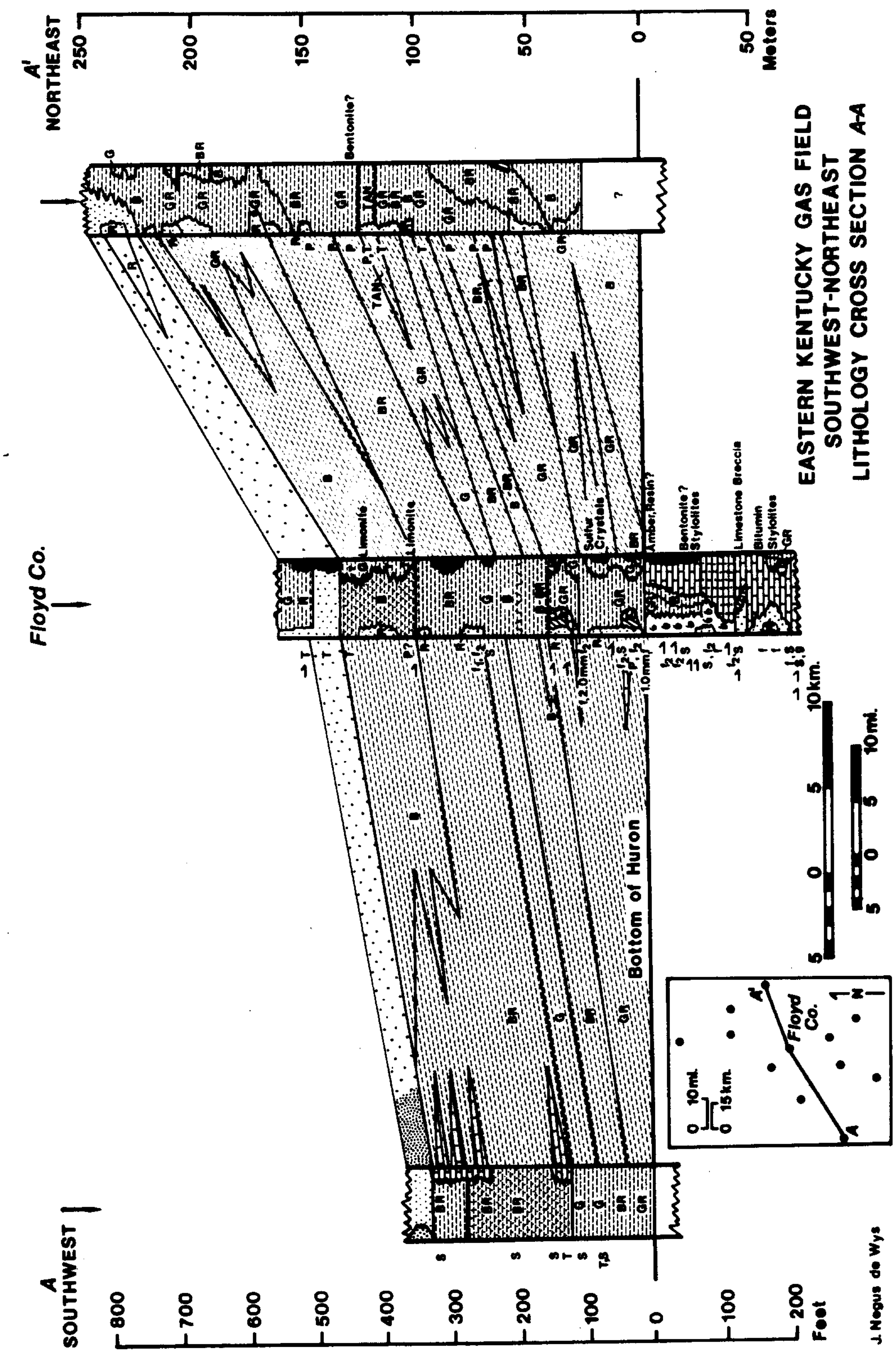

Figure 33. Lithology cross section A-A'.

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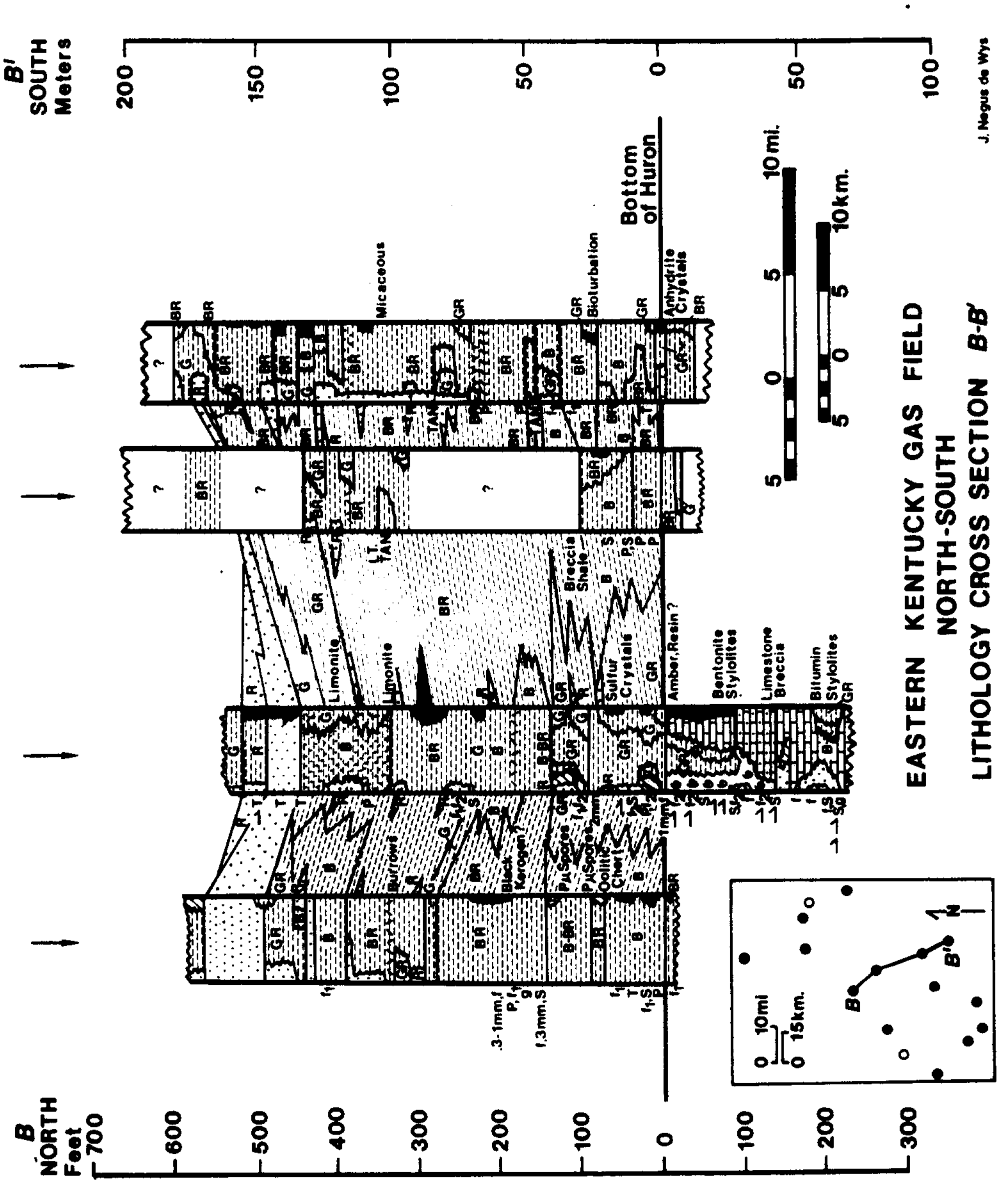

Figure 34. Lithology cross section B-B'.

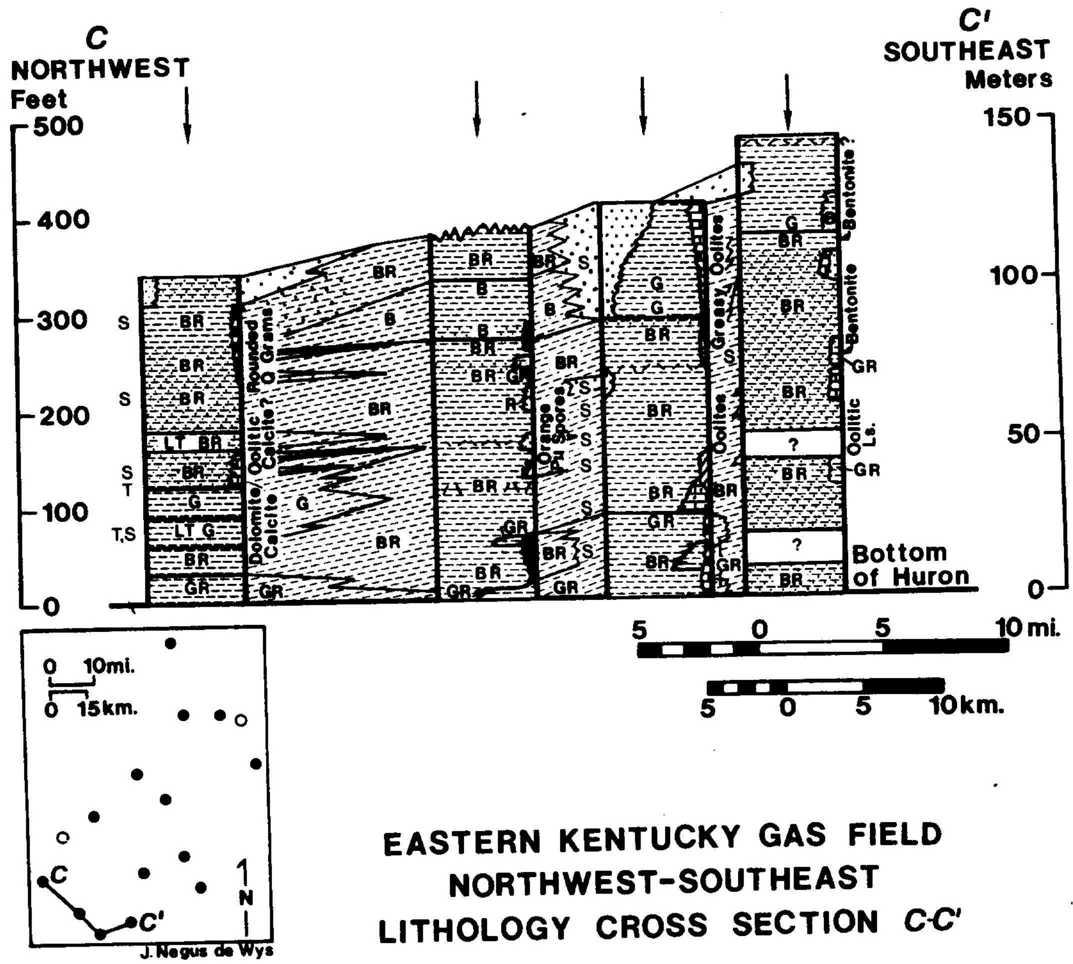

Figure 35. Lithology cross section C-C'.

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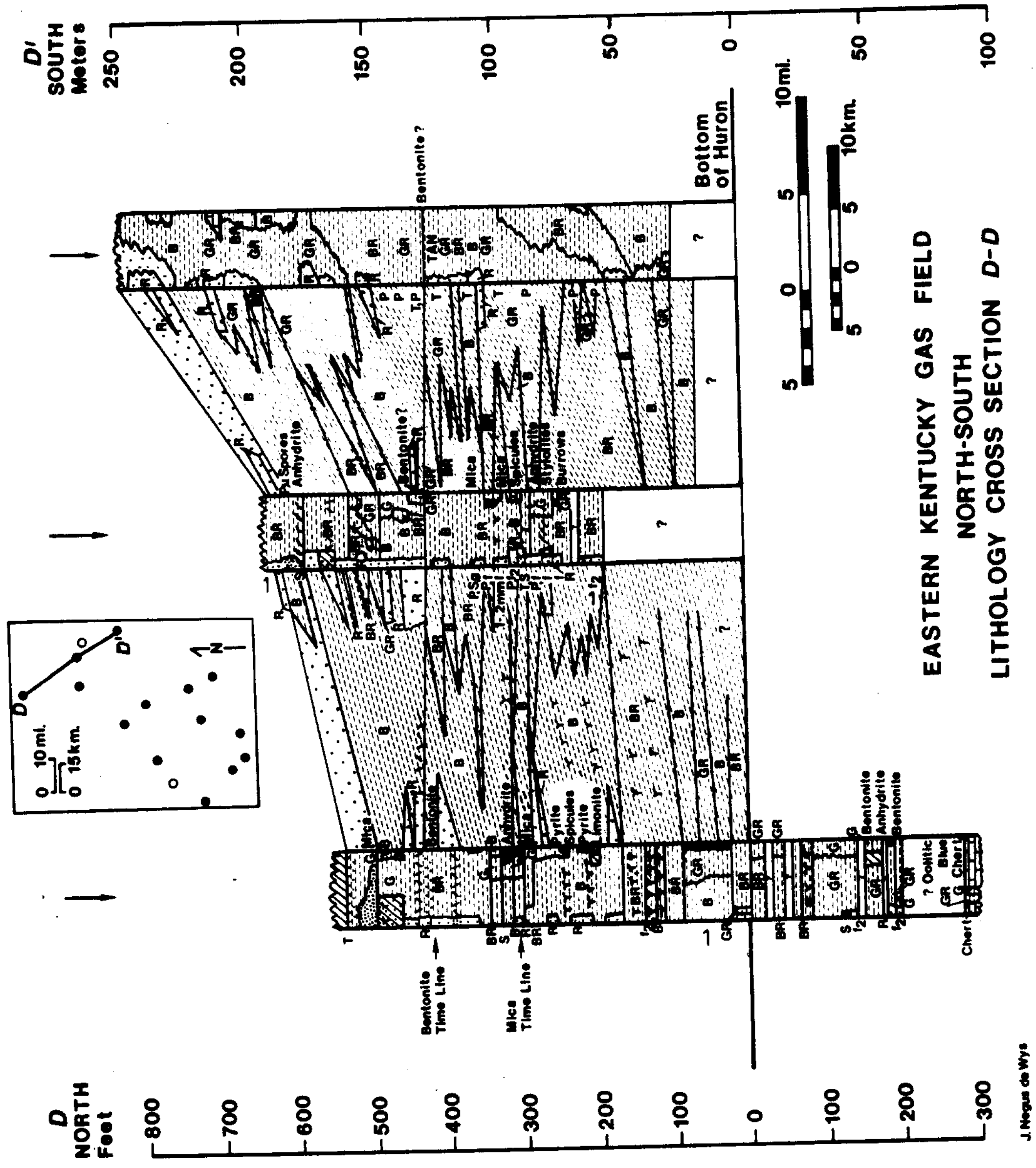

Figure 36. Lithology cross section D-D'.

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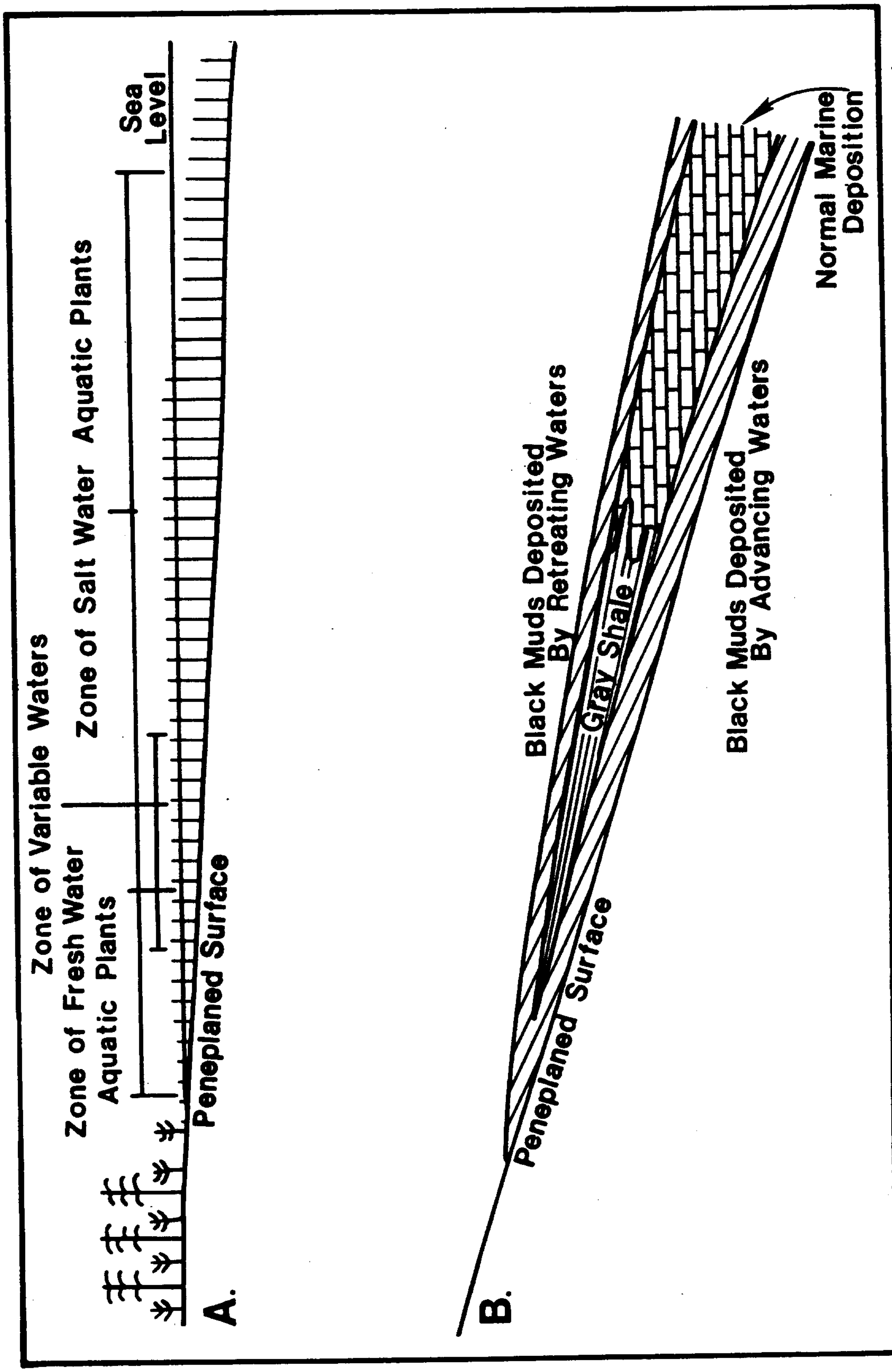
Figure 37a. Drawing of Archaeopteris from Gillespie, et al., 1978, with permission from the West Virginia Geological and Economic Survey. This fern-like tree was placed in a new class Progymnospermopsida in 1971 after the fronds of Callixylon were found attached to the stem of Archaeopteris which is reported from several locales in the Ohio Shale, and is known to exceed a diameter of five feet.

Figure 37b. Deposition of black muds in shallow tideless waters (after Twenhofel, 1939). "A peneplaned surface, or any level surface of any origin, is gradually submerged with plants adjusted to depths. The marginal areas are covered with aquatic plants bathed by fresh waters. Seaward the aquatic plants are bathed by brackish and salt waters. Between the salt-water and fresh-water plants is a zone of variable waters. It is postulated that the plants would hinder and largely prevent circulation, thus insuring deposition of black muds. An advancing sea would leave a deposit of black mud over the area of advance and this would become covered by other deposits as the waters become too deep for the plants to thrive. A receding sea would leave a deposit of black mud over the areas deserted." (Twenhofel, 1939).



(after Twenhofel, 1939)

Figure 37b. (Caption on preceding page.)

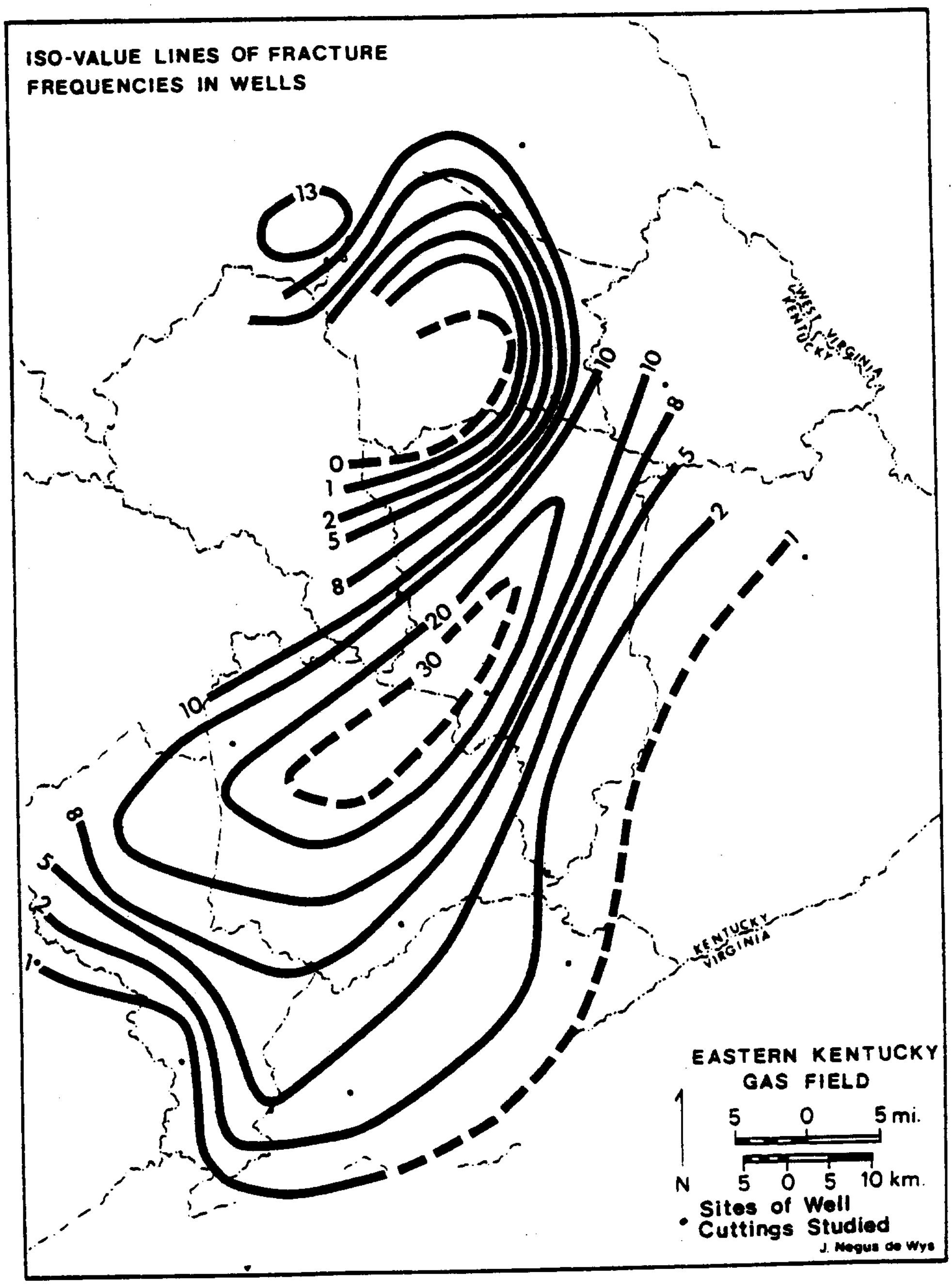


Figure 38. Map of observed frequency of fracture horizons in wells studied.

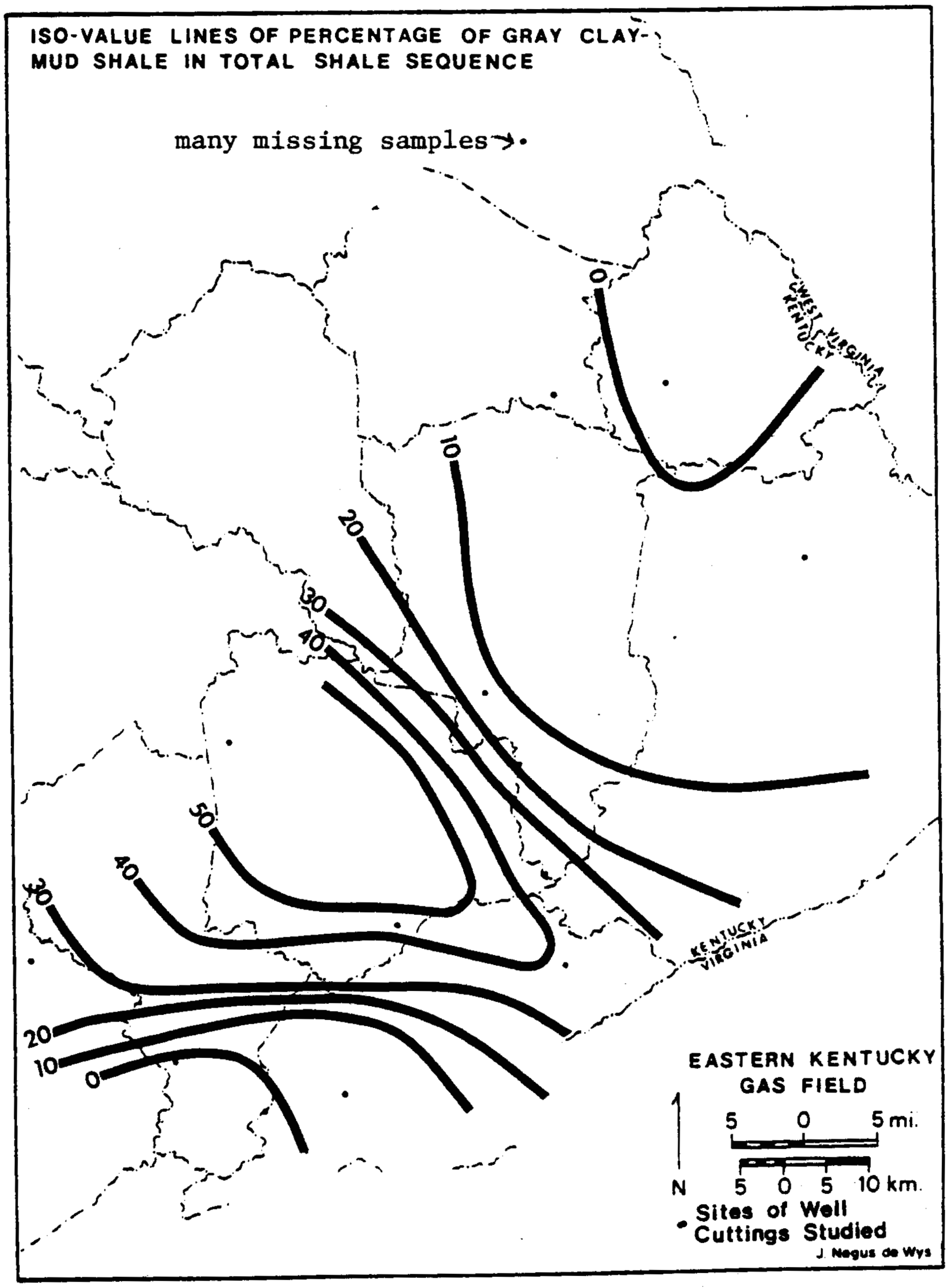


Figure 39. Map showing iso-value lines of percent gray clay- to mud-shale of total sequence.

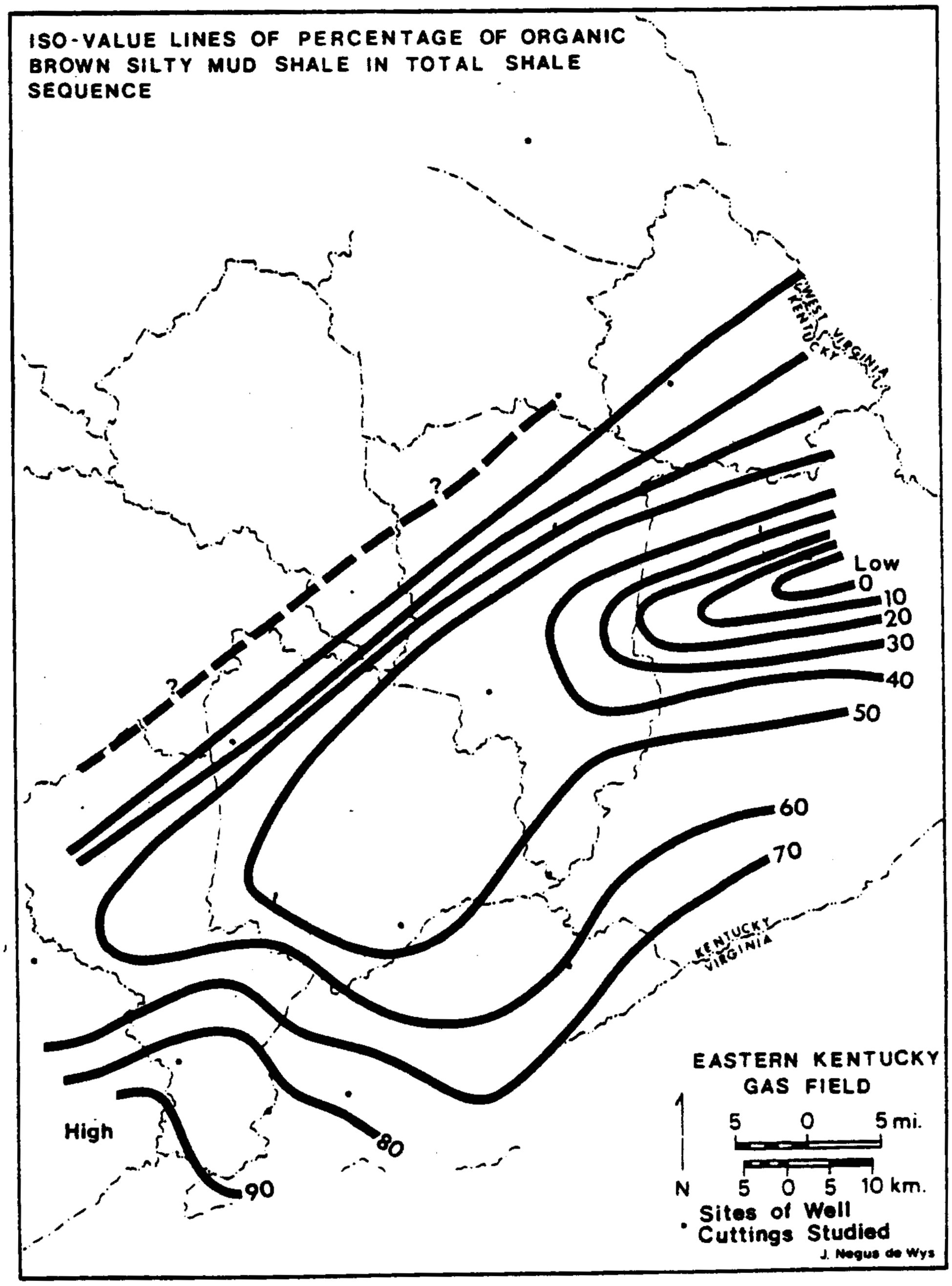


Figure 40. Map showing iso-value lines of percent organic brown silty mud-shale of total shale sequence.

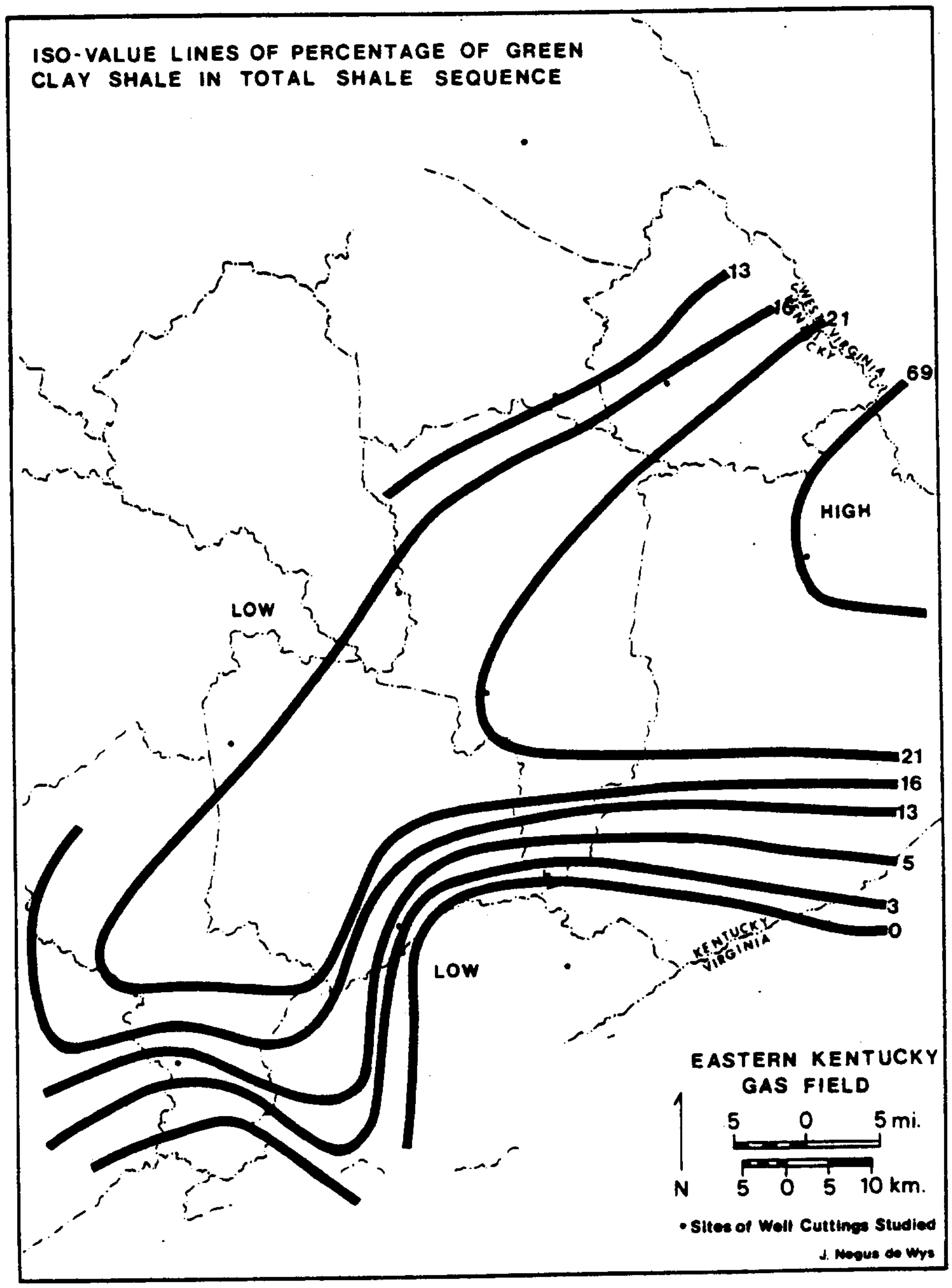


Figure 41. Map showing iso-value lines of percent green clay-shale of total shale sequence.

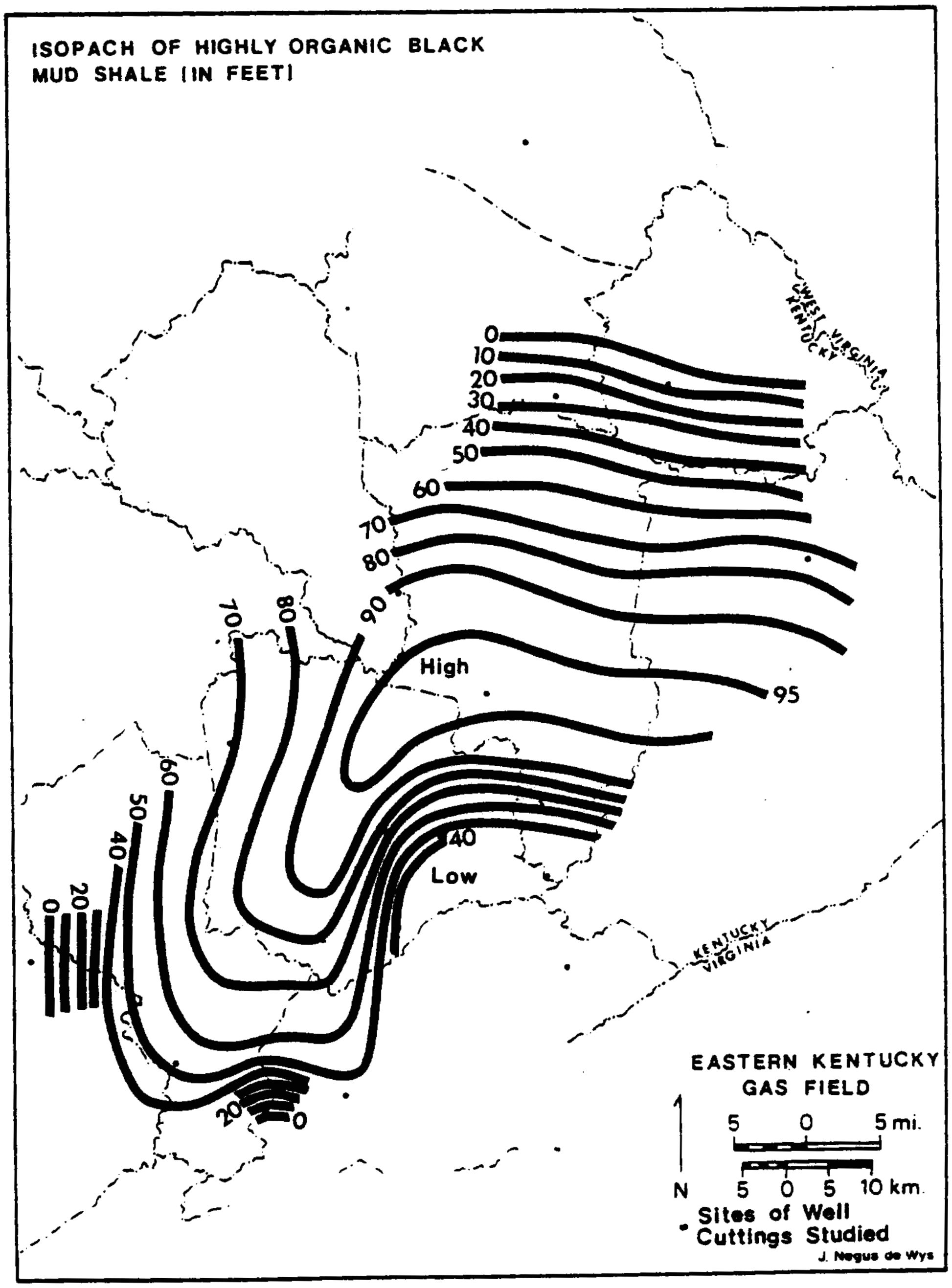


Figure 42. Isopach map of highly organic black mud-shale (in feet).

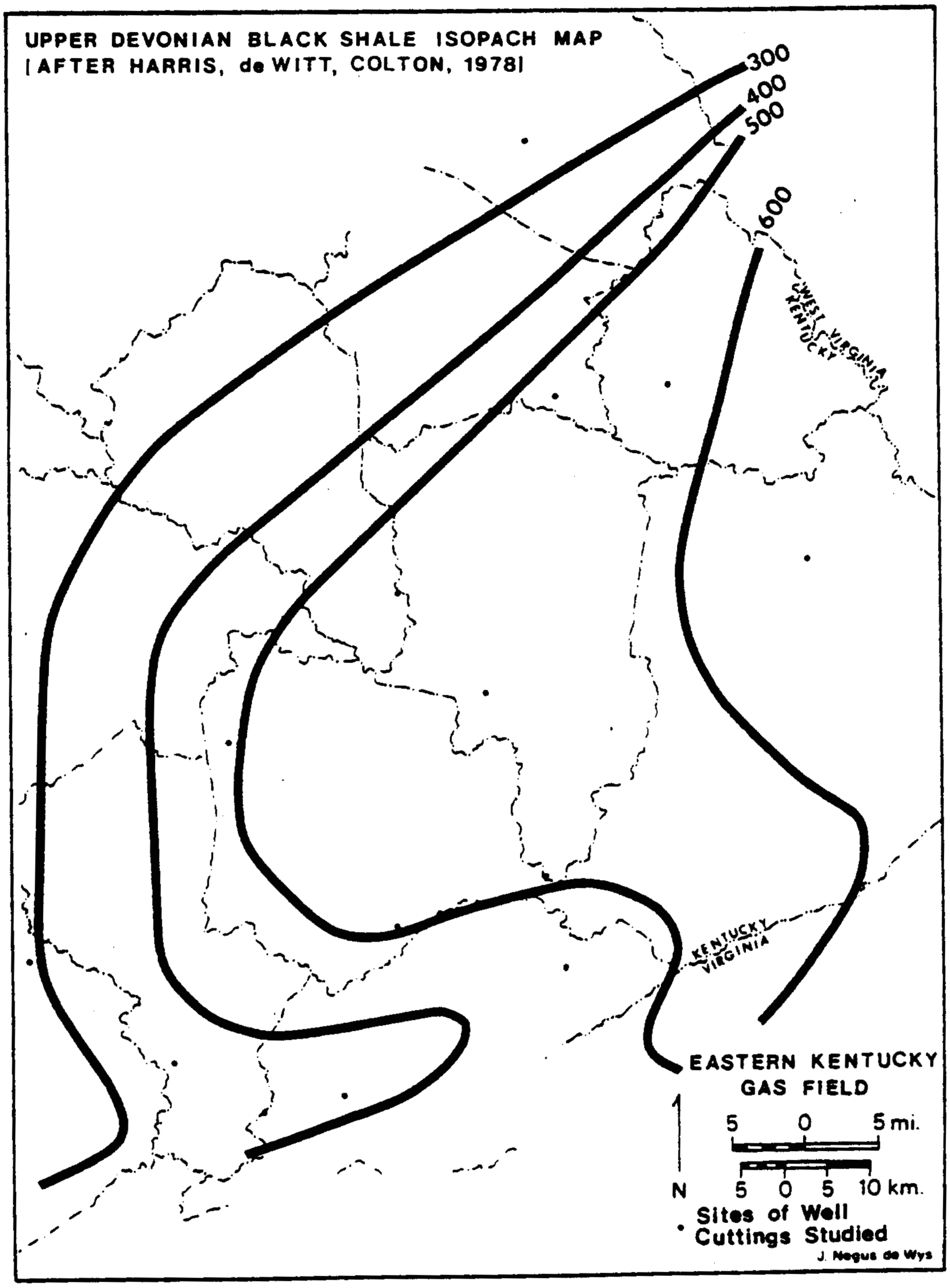


Figure 43. Upper Devonian black shale isopach map (after Harris, de Witt, Jr., and Colton, 1978). Contours in feet.

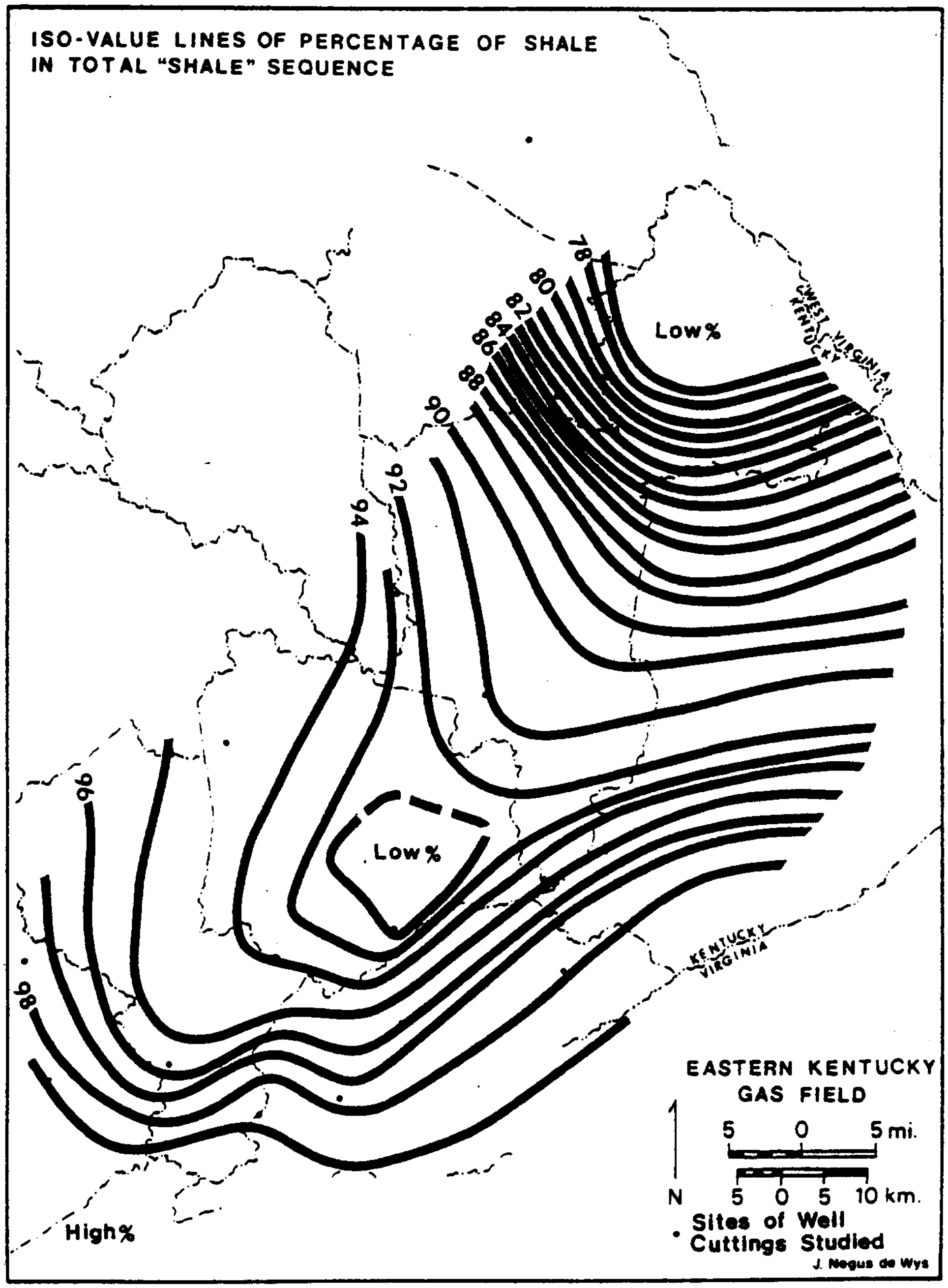


Figure 44. Map showing iso-value lines of percent shale in total shale sequence.

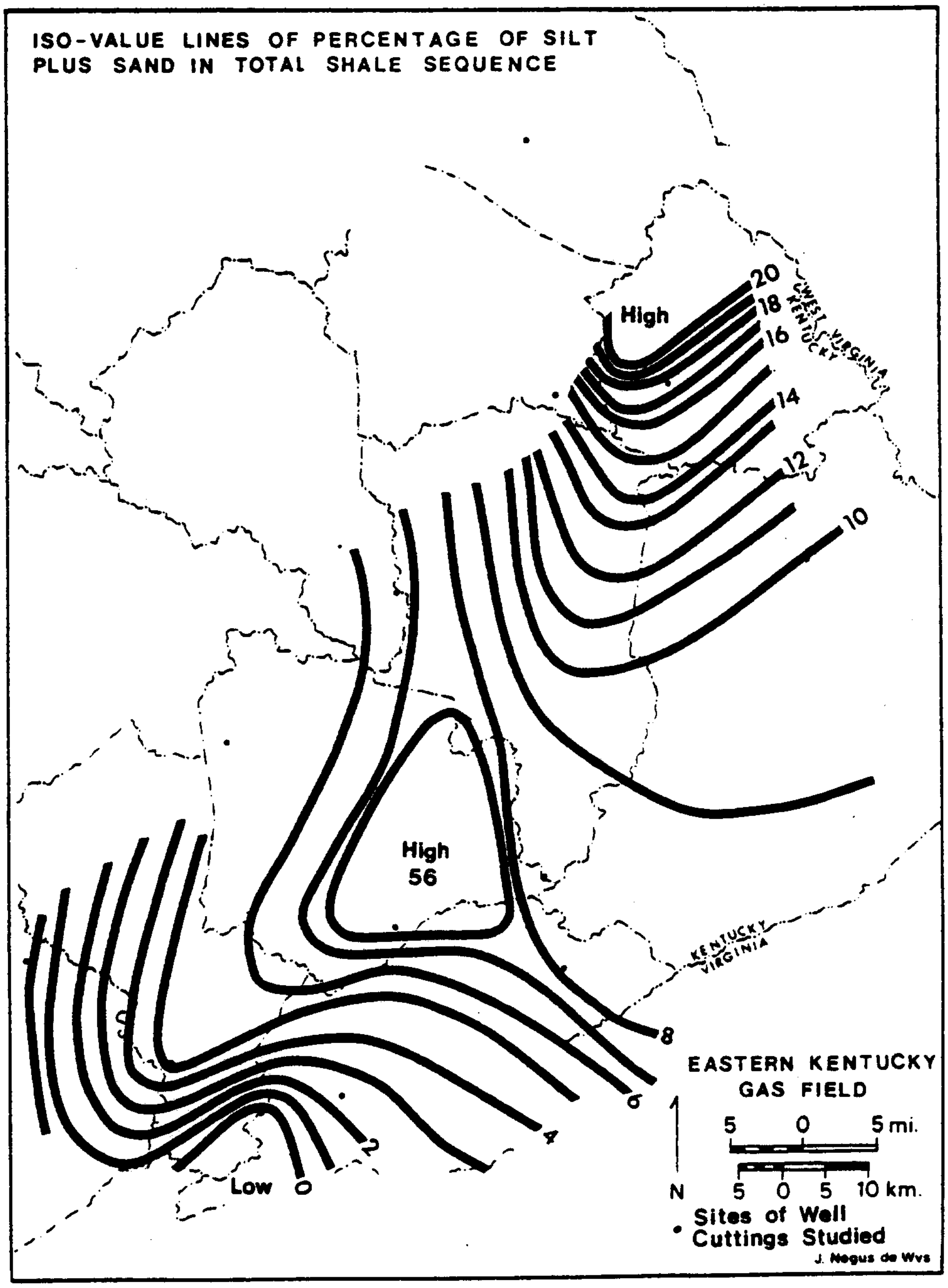


Figure 45. Map showing lines of percent silt plus sand in total shale sequence.

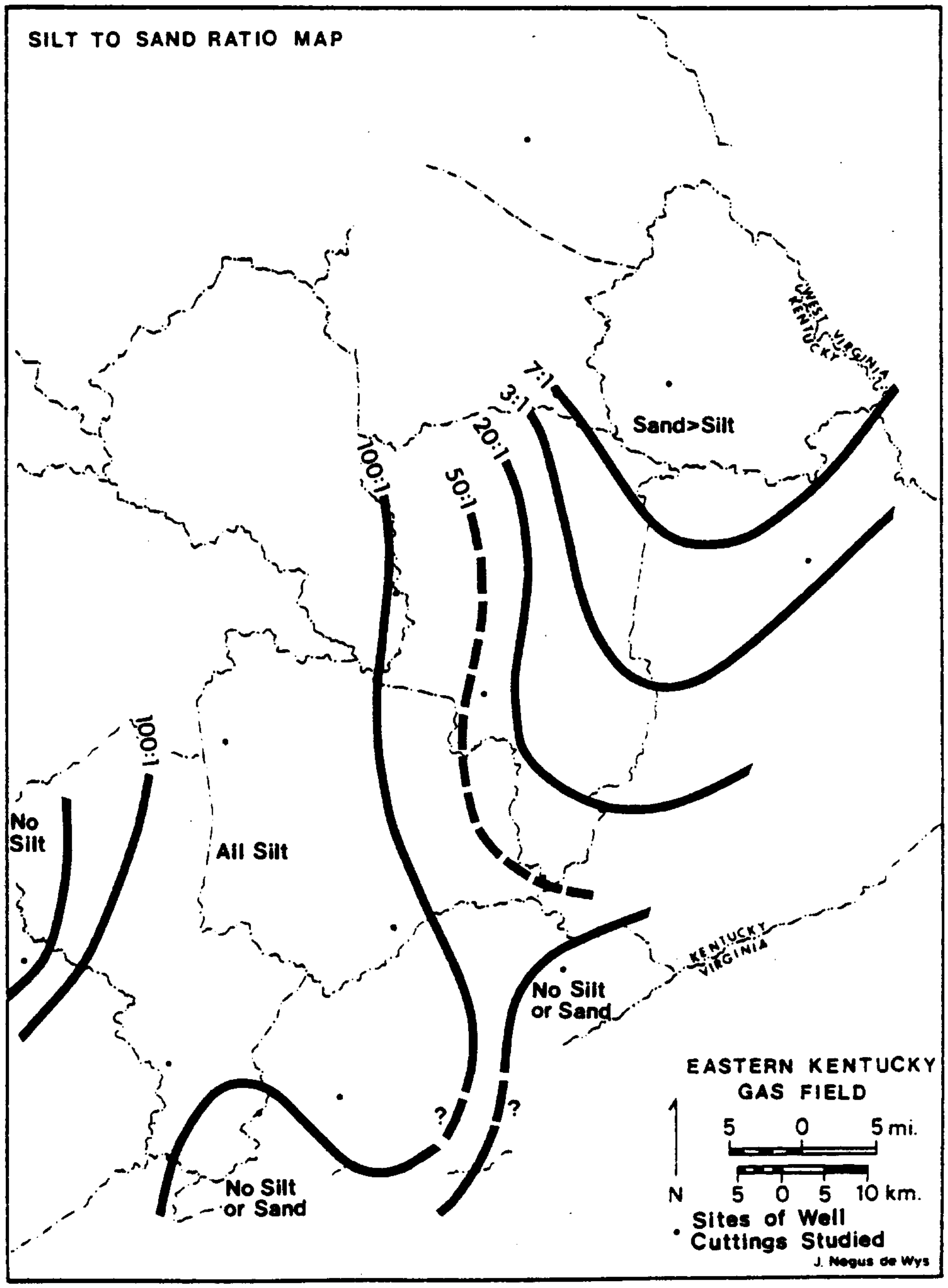


Figure 46. Silt to sand ratio map.

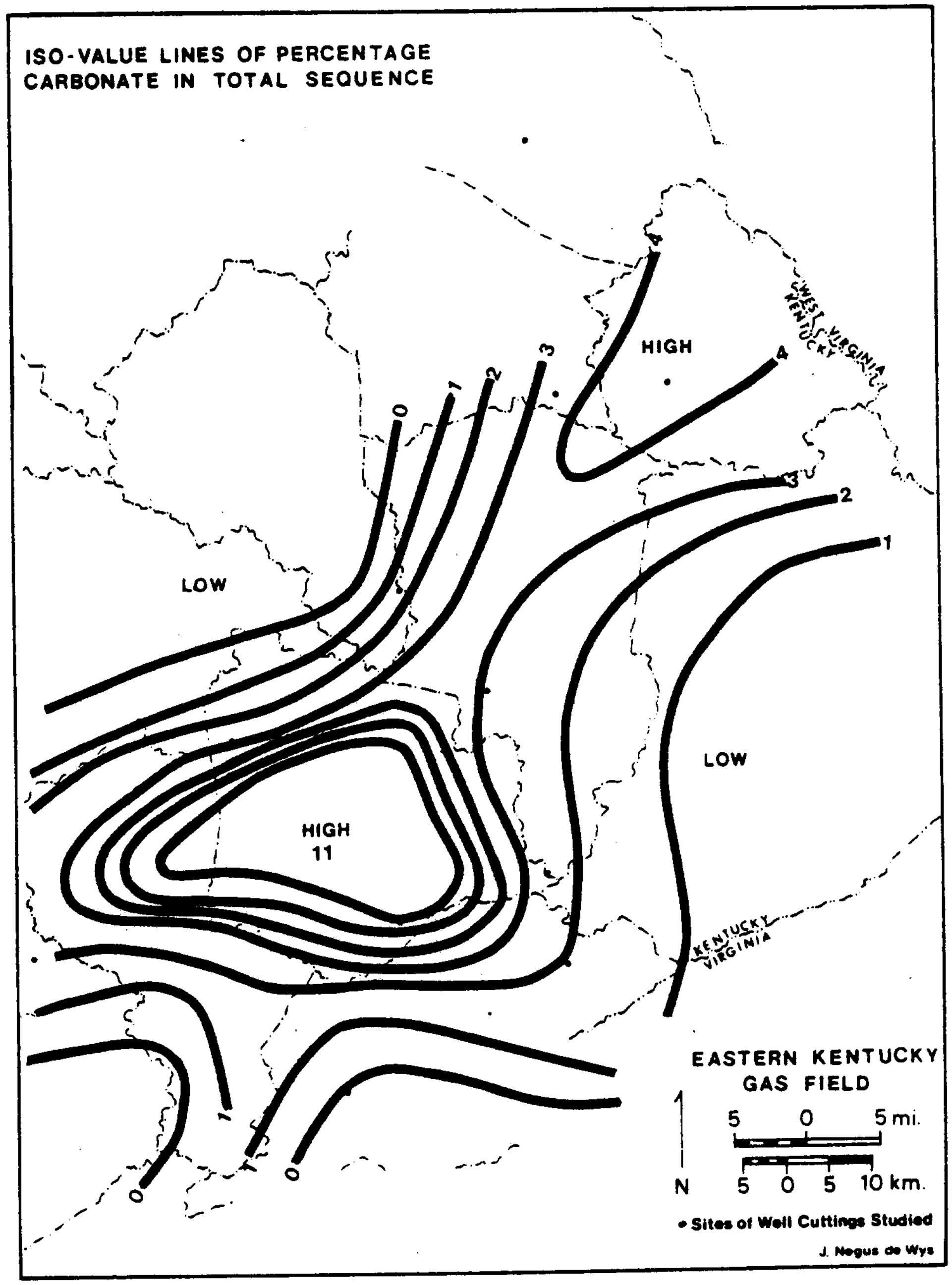


Figure 47. Map showing iso-value lines of percent carbonate in total sequence.

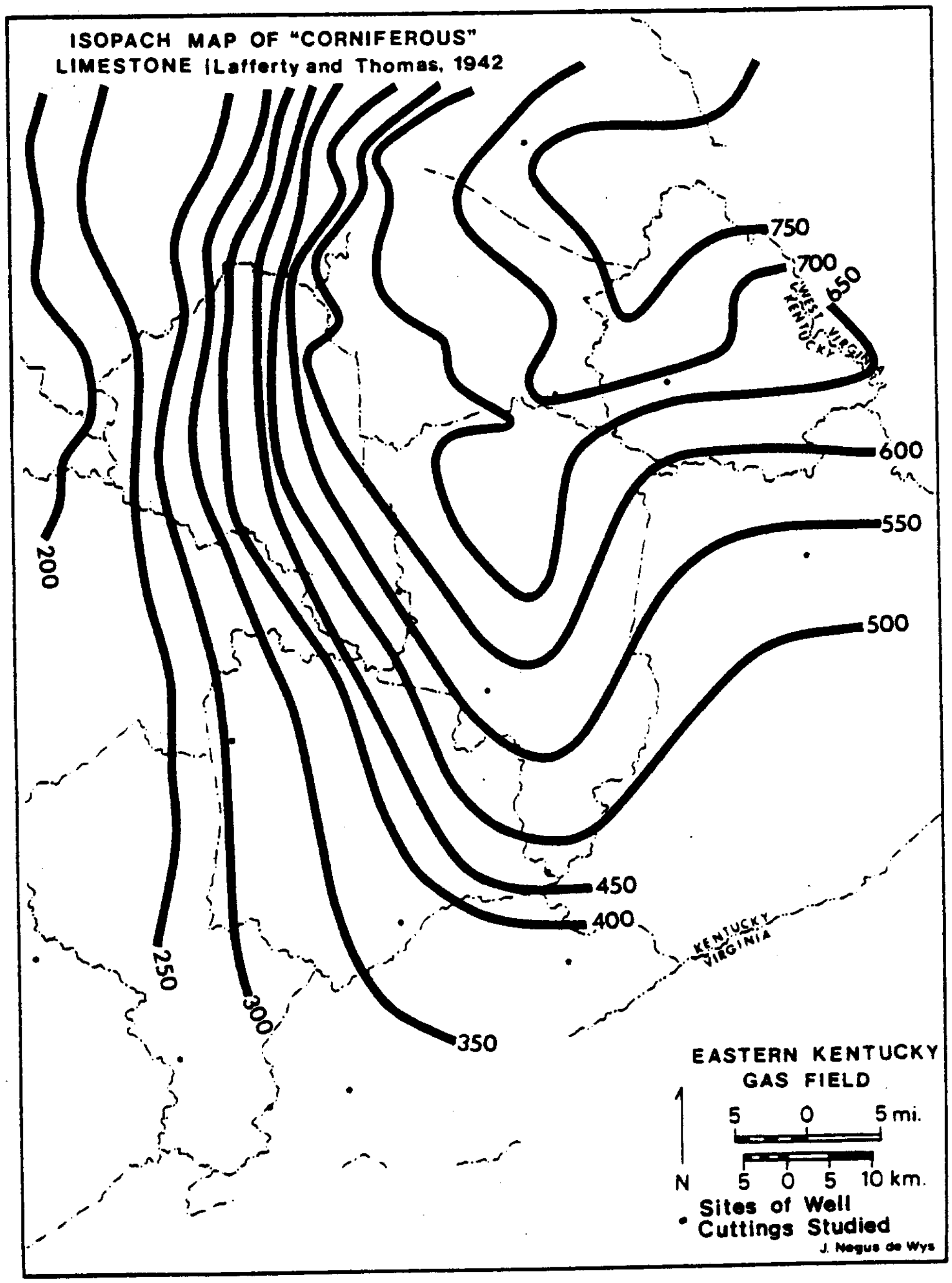


Figure 48. Isopach map of "Corniferous" limestone (McFarlan, 1943). Contours in feet.

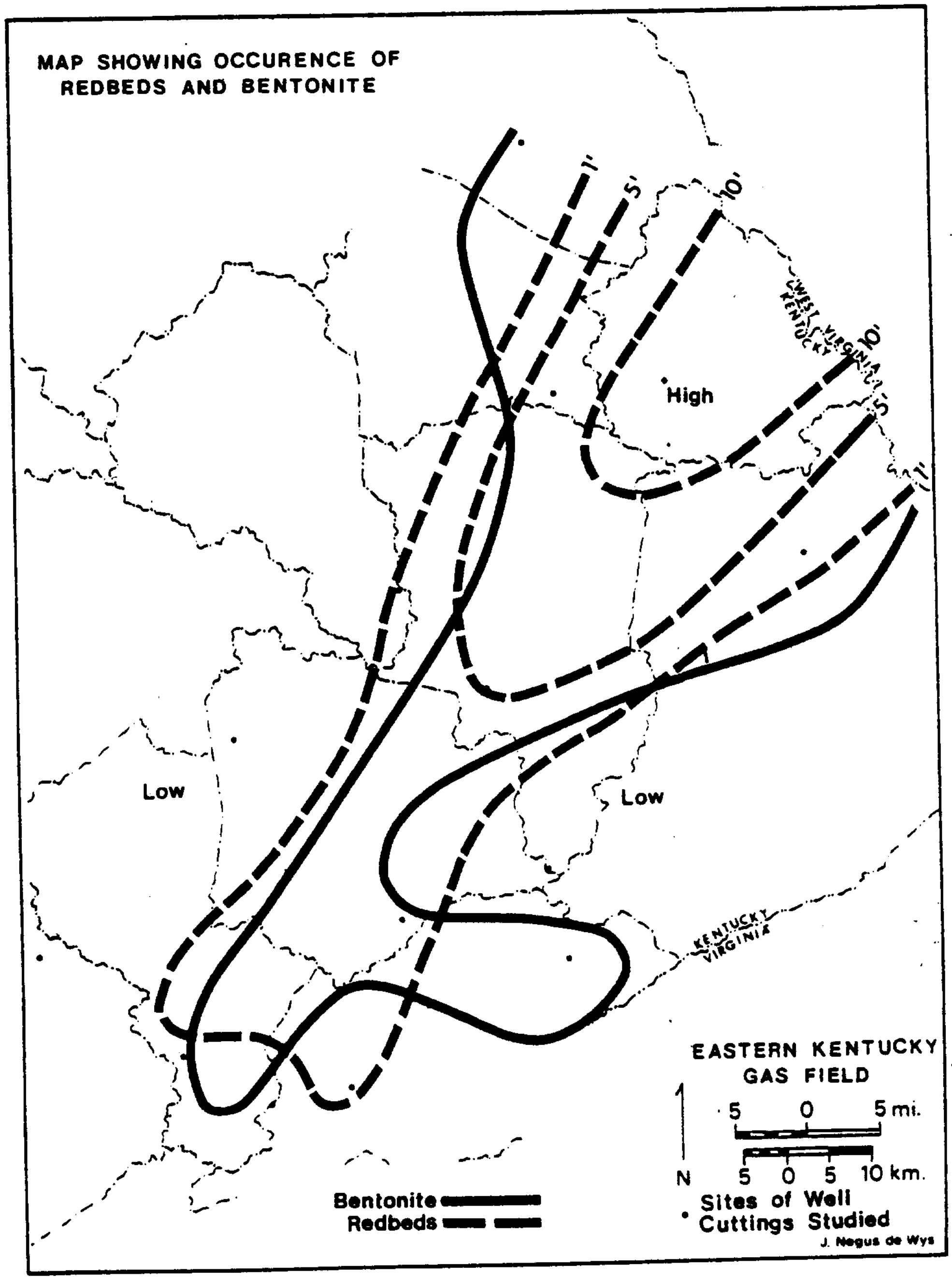


Figure 49. Map showing occurrence of redbeds and bentonites. Contours in feet.

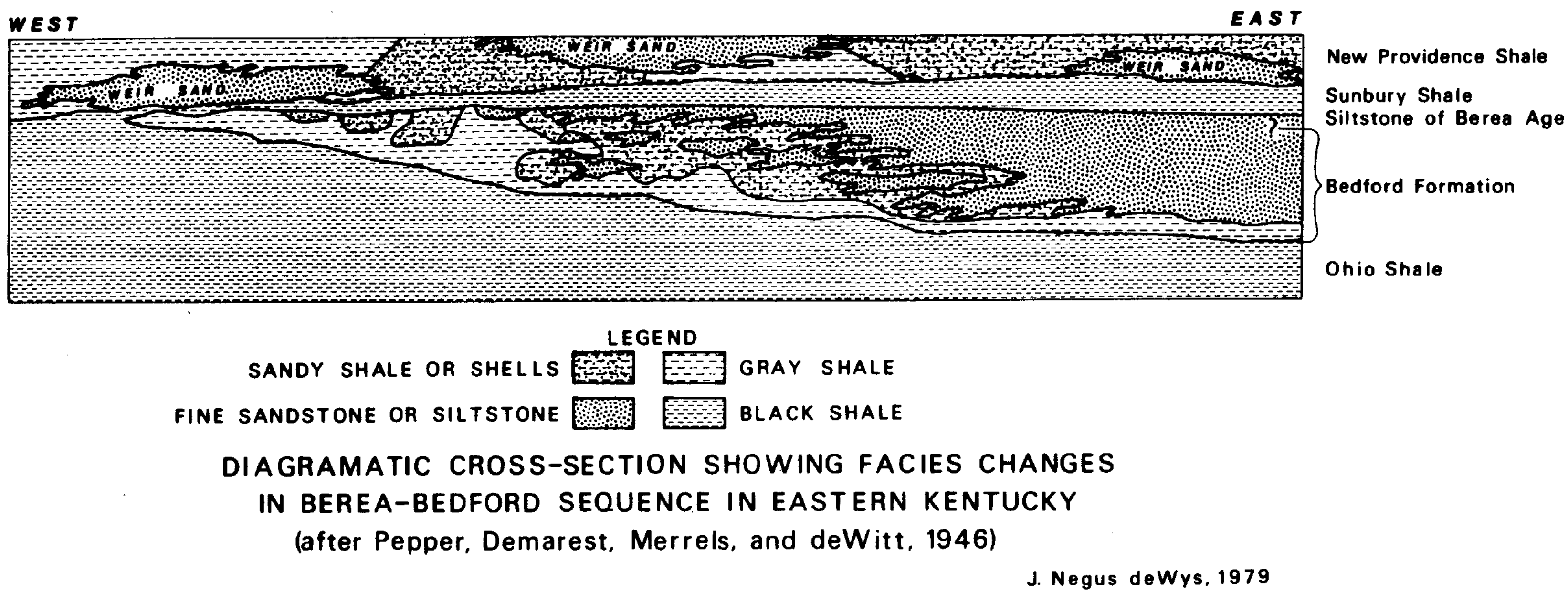


Figure 50. Diagramatic cross section showing facies changes in the Berea/Bedford sequence in eastern Kentucky (after Pepper et al., 1946). The cause of these changes is not completely understood.

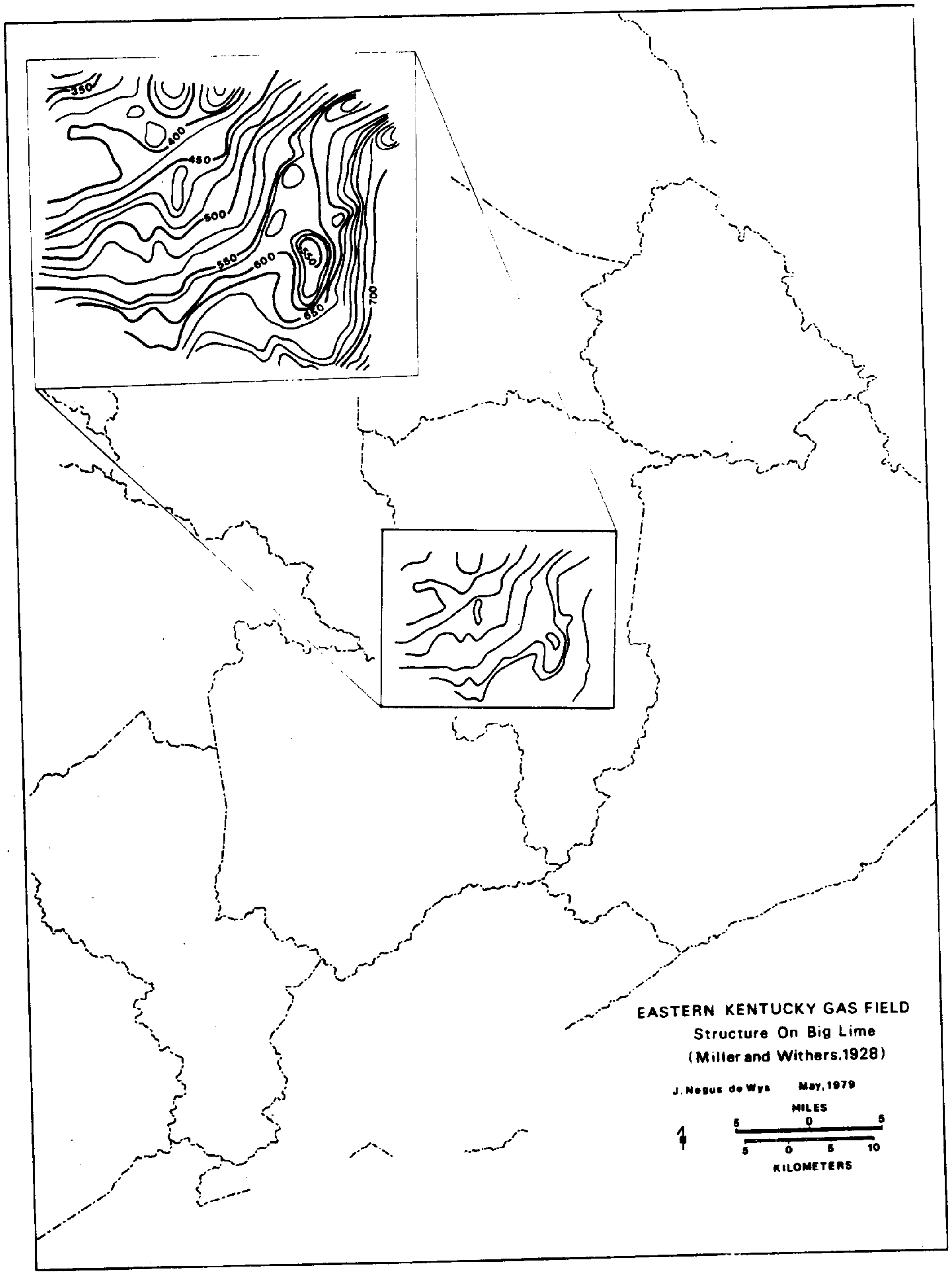


Figure 51. Structure on the Big Lime (after Miller and Withers, 1928).

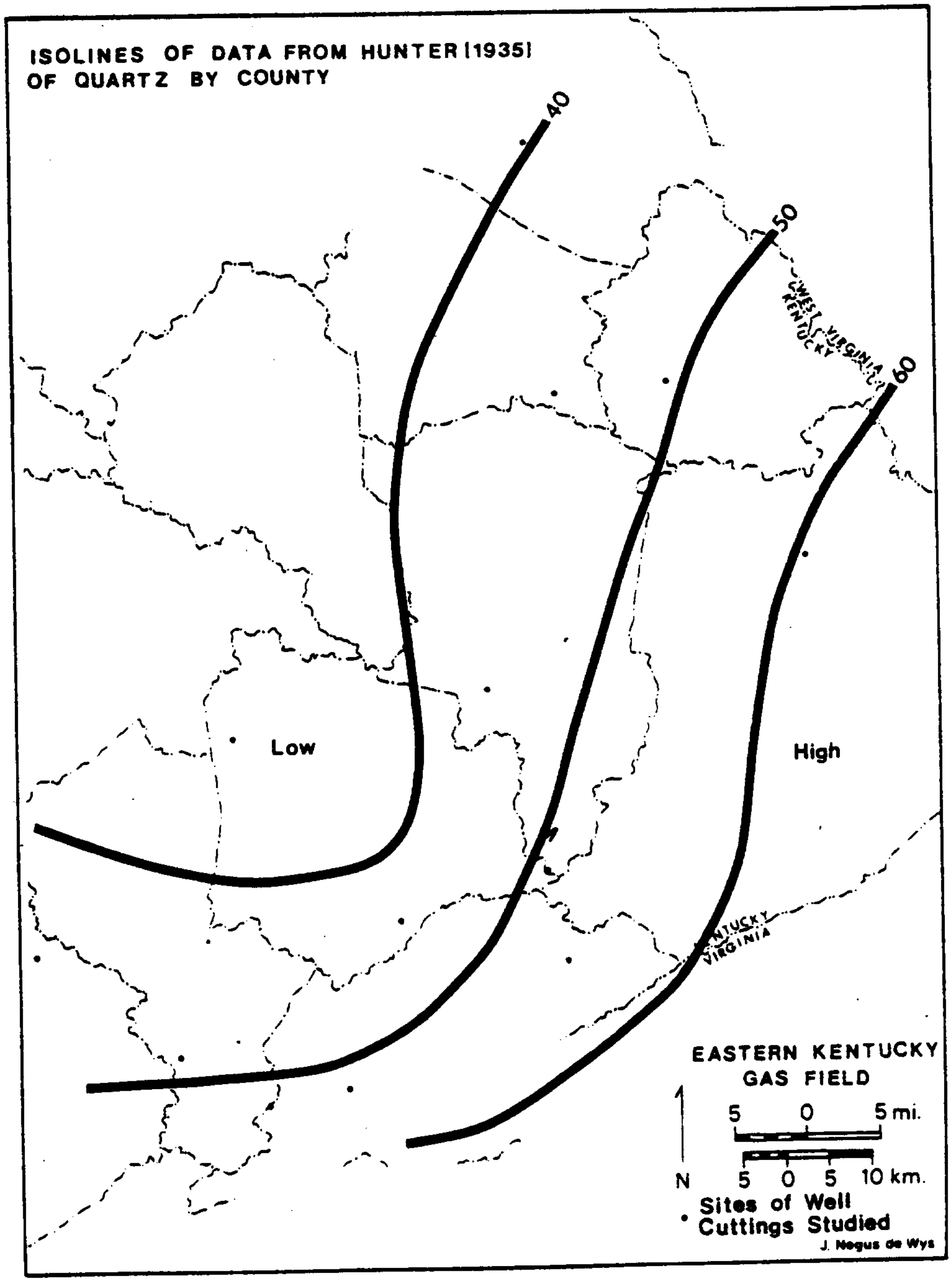


Figure 52. Isolines drawn on quartz data from Hunter (1935). Data values are based on published county averages in percent.

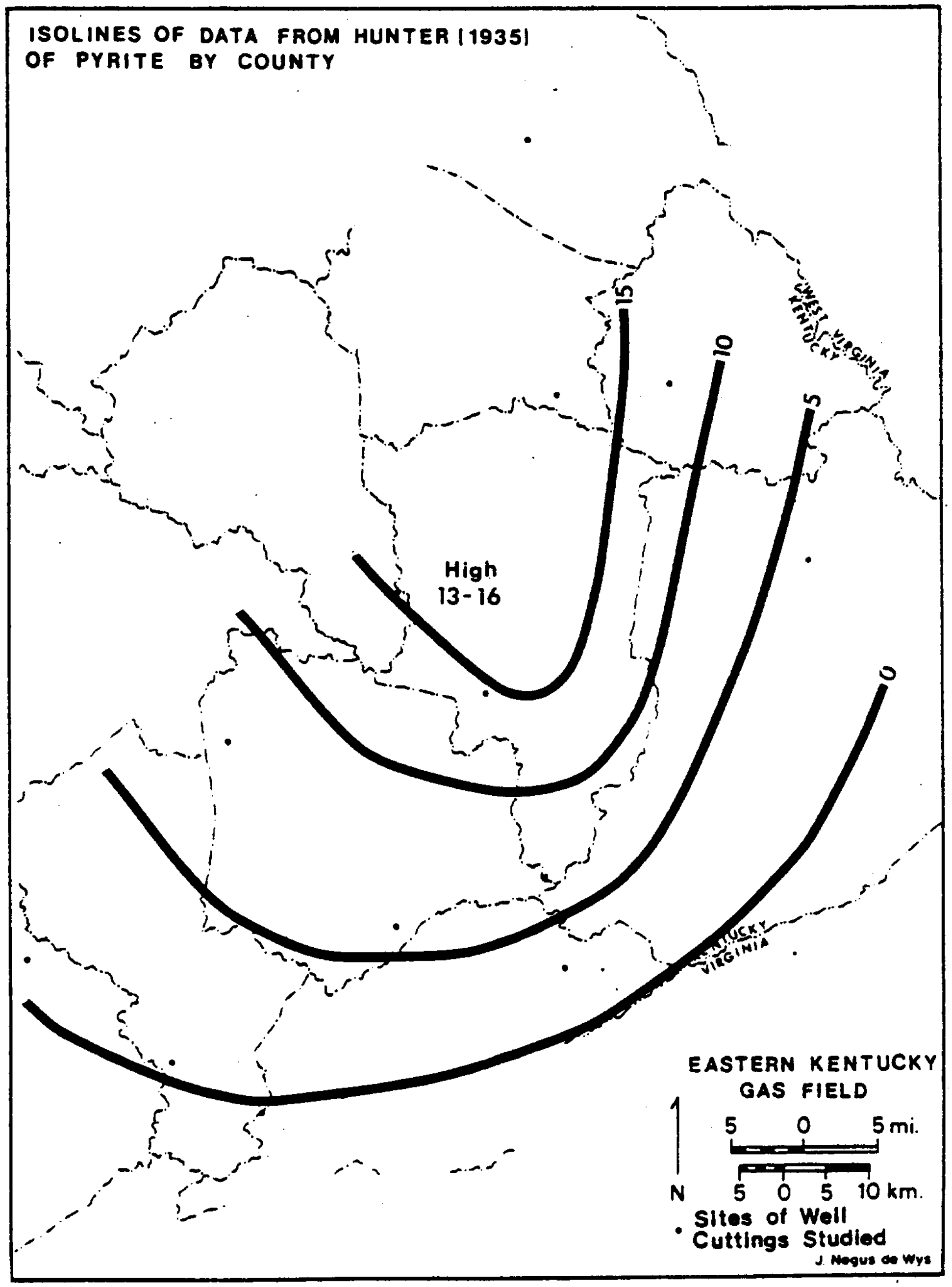


Figure 53. Isolines drawn on pyrite data from Hunter (1935). Data values are based on published county averages in percent.

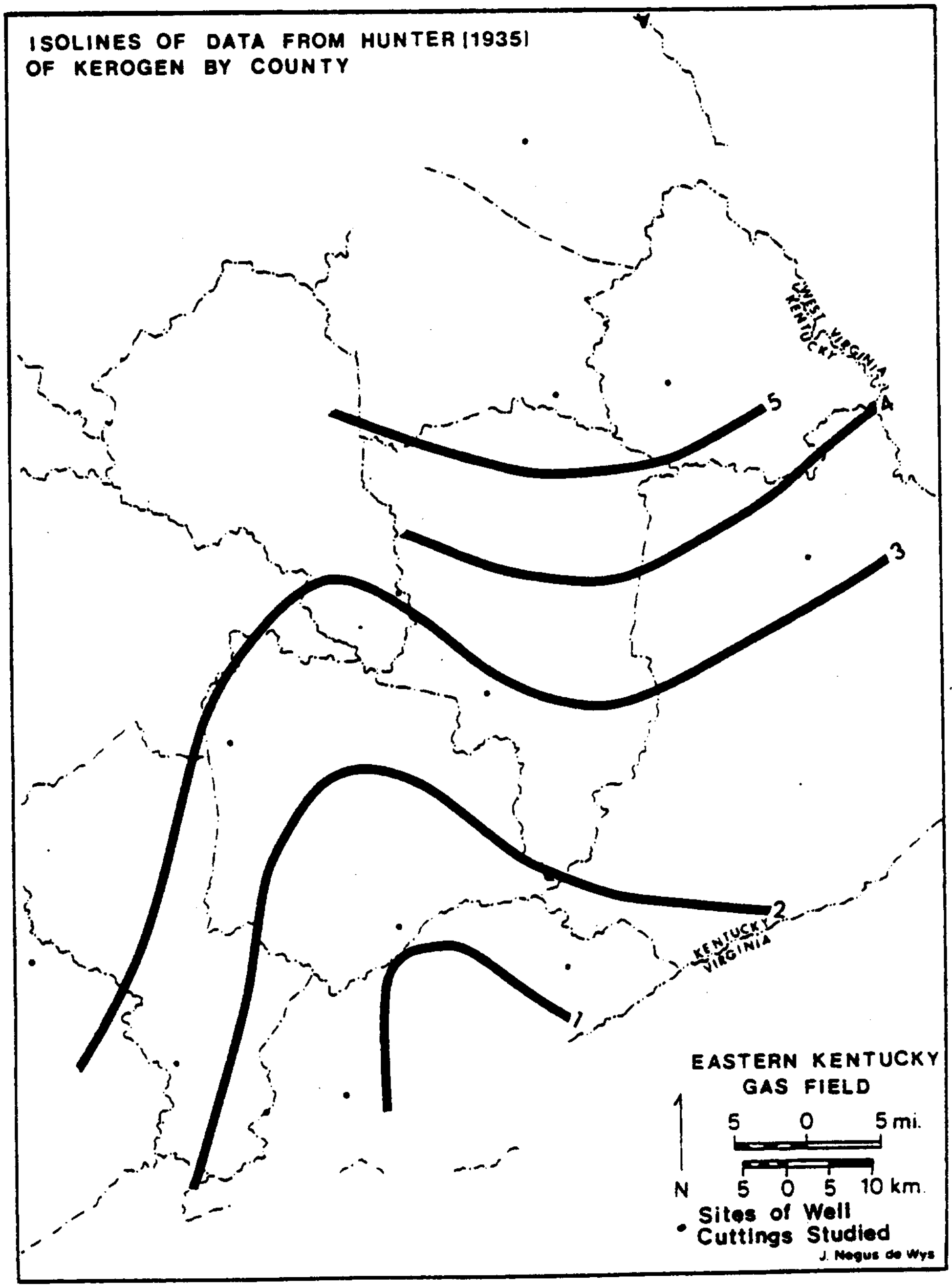


Figure 54. Isolines drawn on kerogen data from Hunter (1935). Data values are based on published county averages in percent.

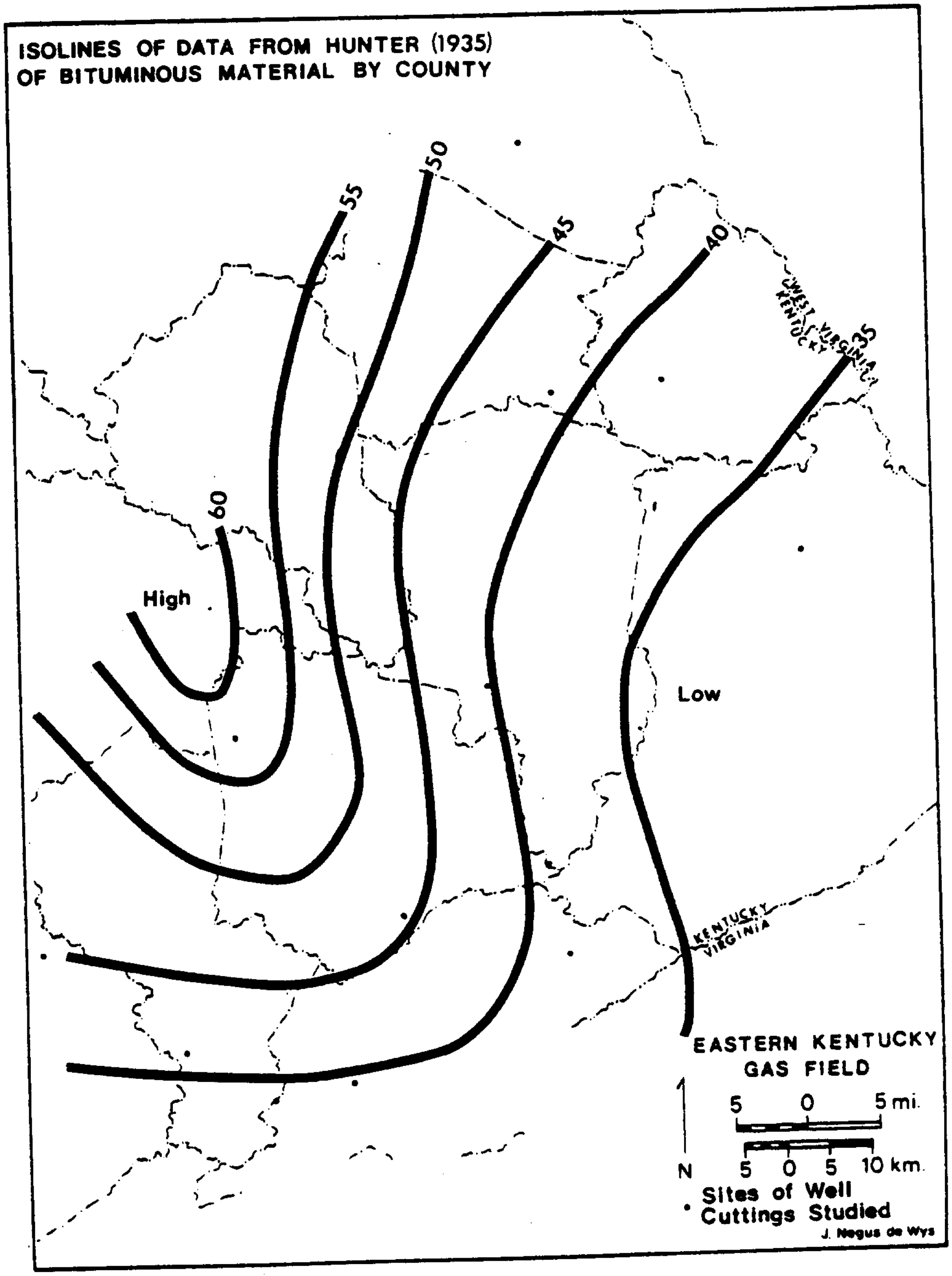


Figure 55. Isolines drawn on bituminous material data from Hunter (1935). Data values are based on published county averages in percent.

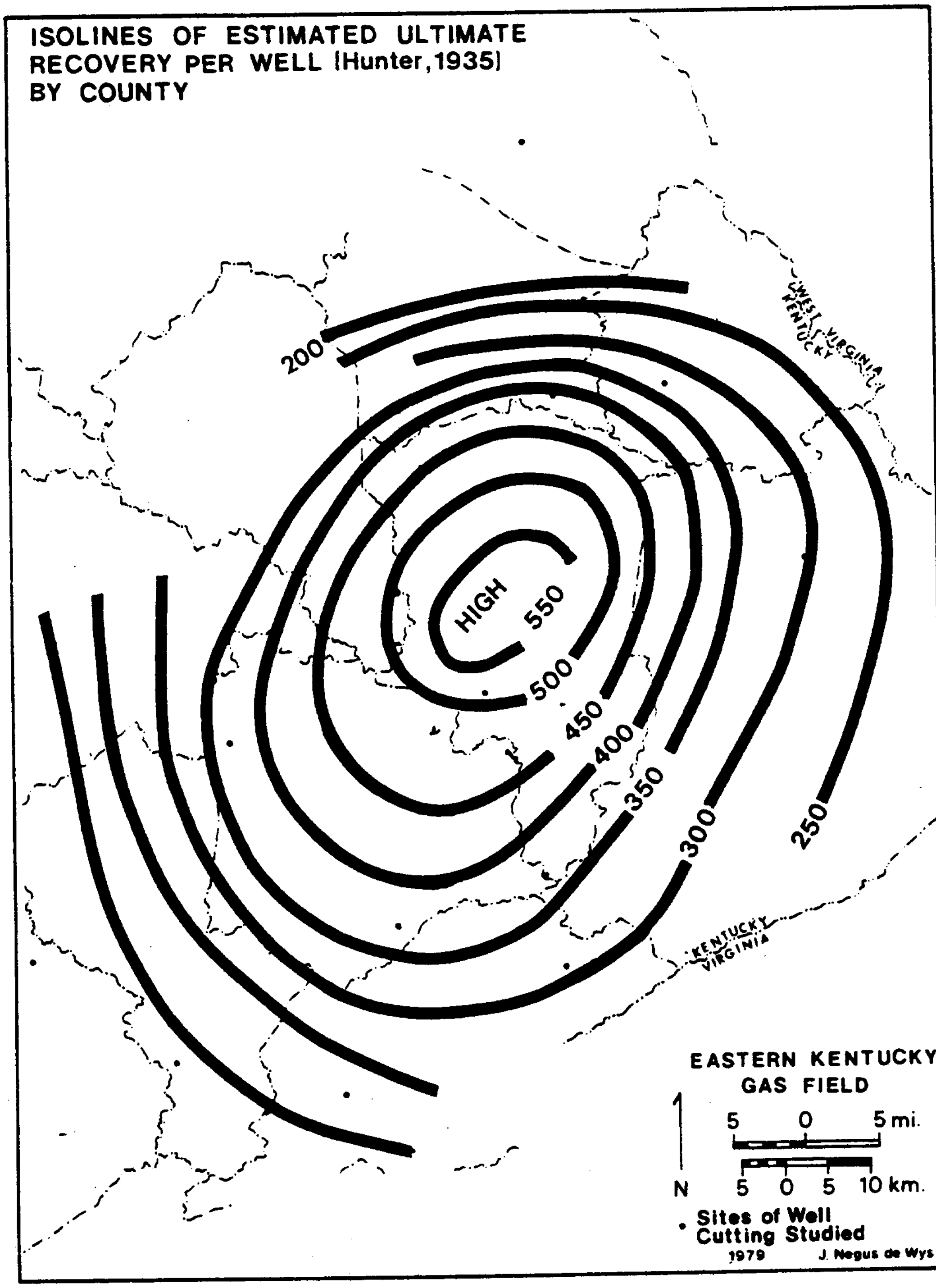


Figure 56. Isolines drawn on estimated ultimate recovery well data (Hunter, 1935). Data values are based on published county averages.

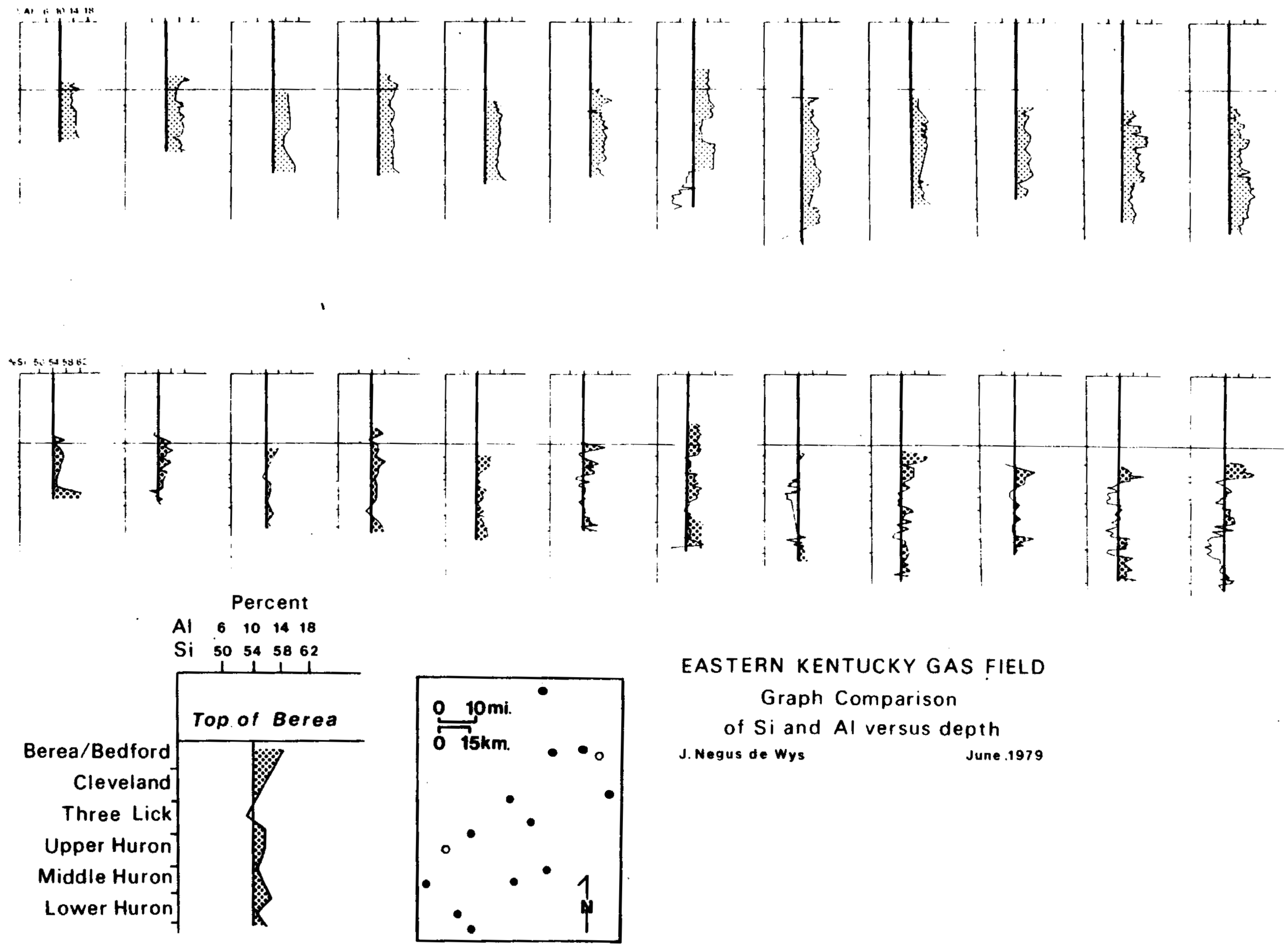


Figure 57. Comparison of Si and Al oxide graphs for the Berea-Bedford through Huron sequence. Wells are arranged west to east from left to right.

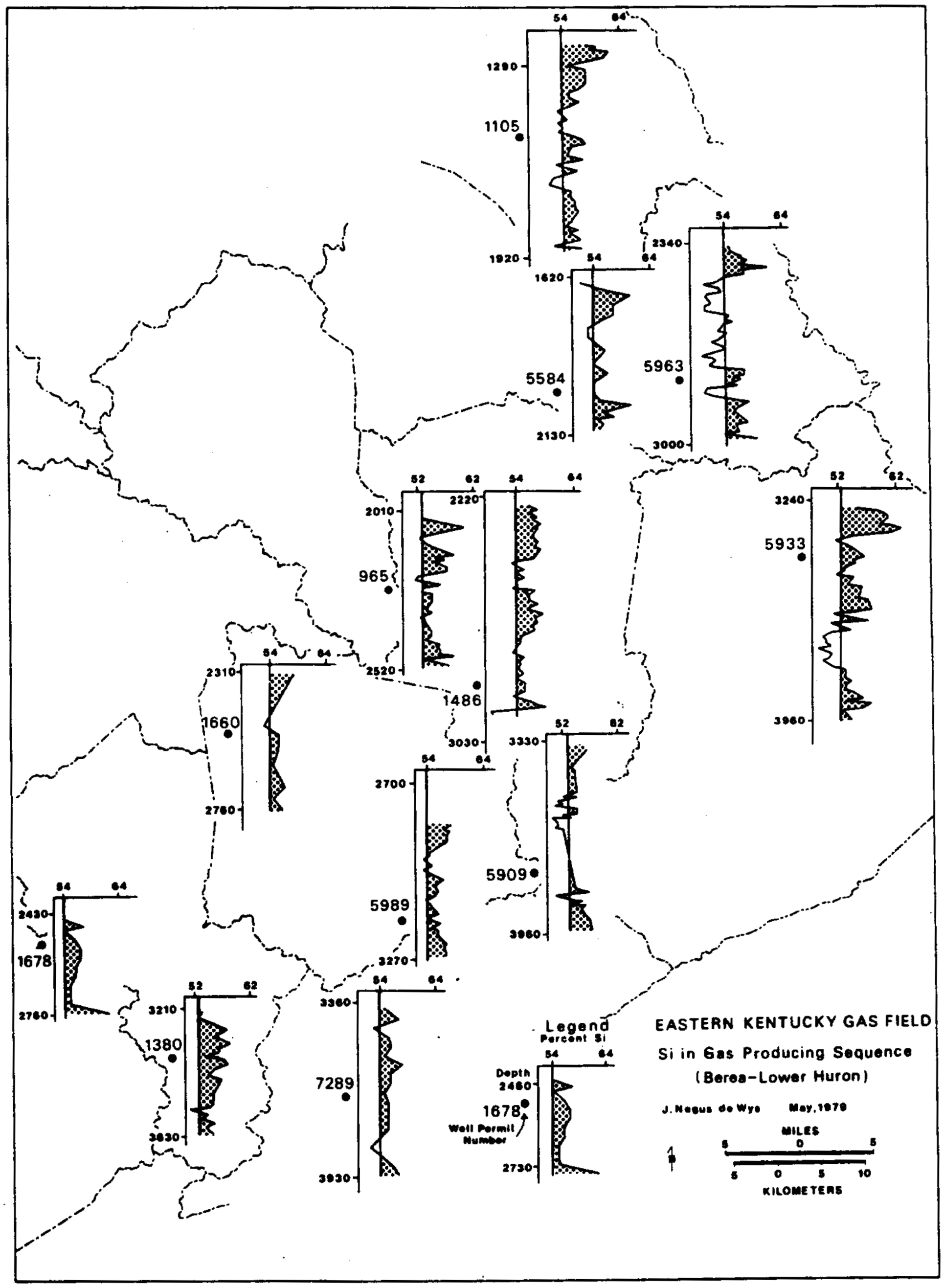


Figure 58. Si oxide graphs in well positions.

LEGEND for Si/Al RATIO CROSS SECTIONS

↓	WELL LOCATION on CROSS SECTION
B/B	TOP of BEREA/BEDFORD
O/C	OHIO SHALE/TOP of CLEVELAND
3 L	TOP of THREE LICK
U H	TOP of UPPER HURON
MH	TOP of MIDDLE HURON
L H	TOP of LOWER HURON
H B	BOTTOM of HURON
	>4.0 Si/Al OXIDE RATIO
•	STUDY WELLS
○	CORED WELLS

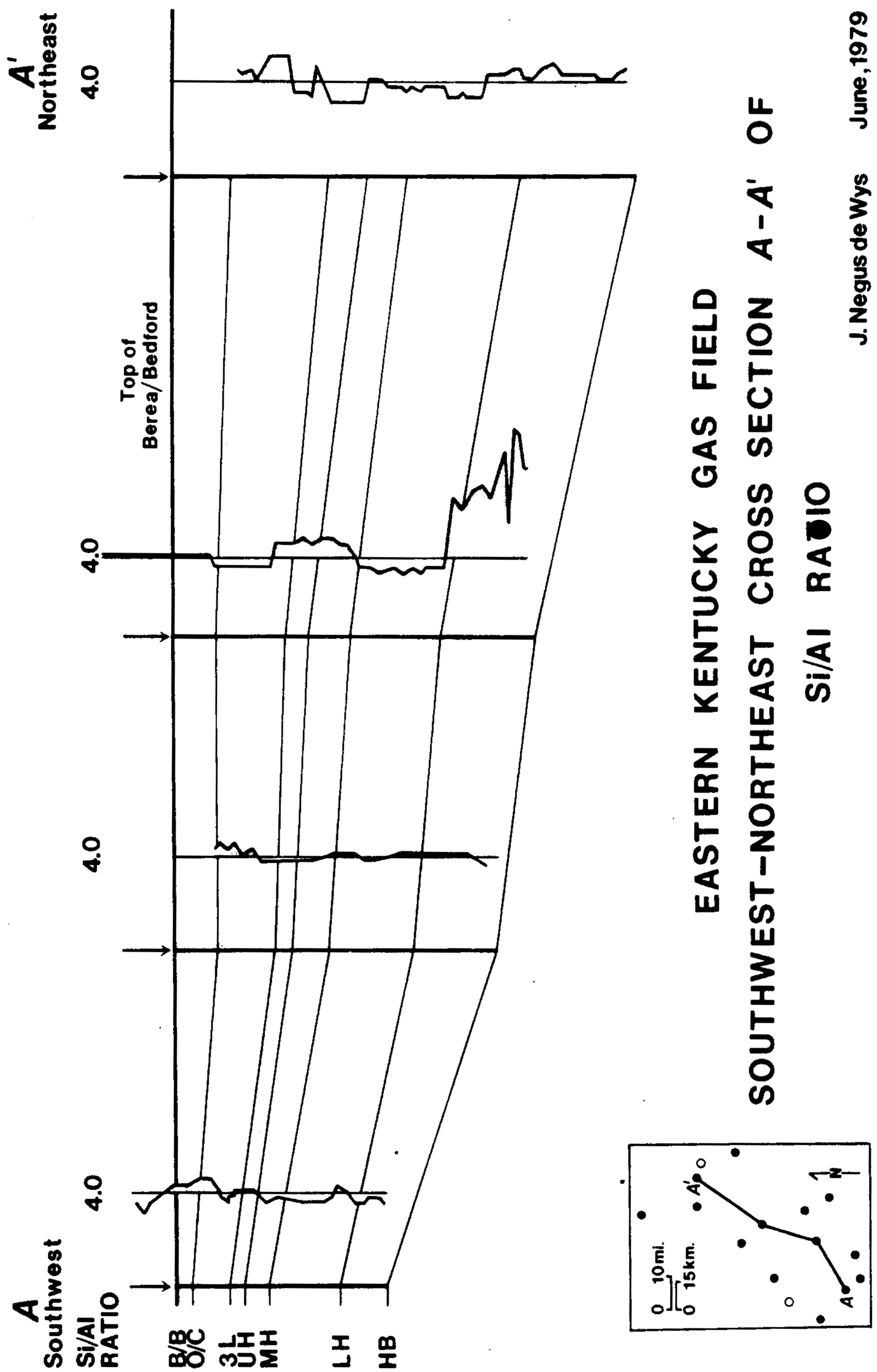


Figure 59. Si/Al oxide ratio cross section A-A'.

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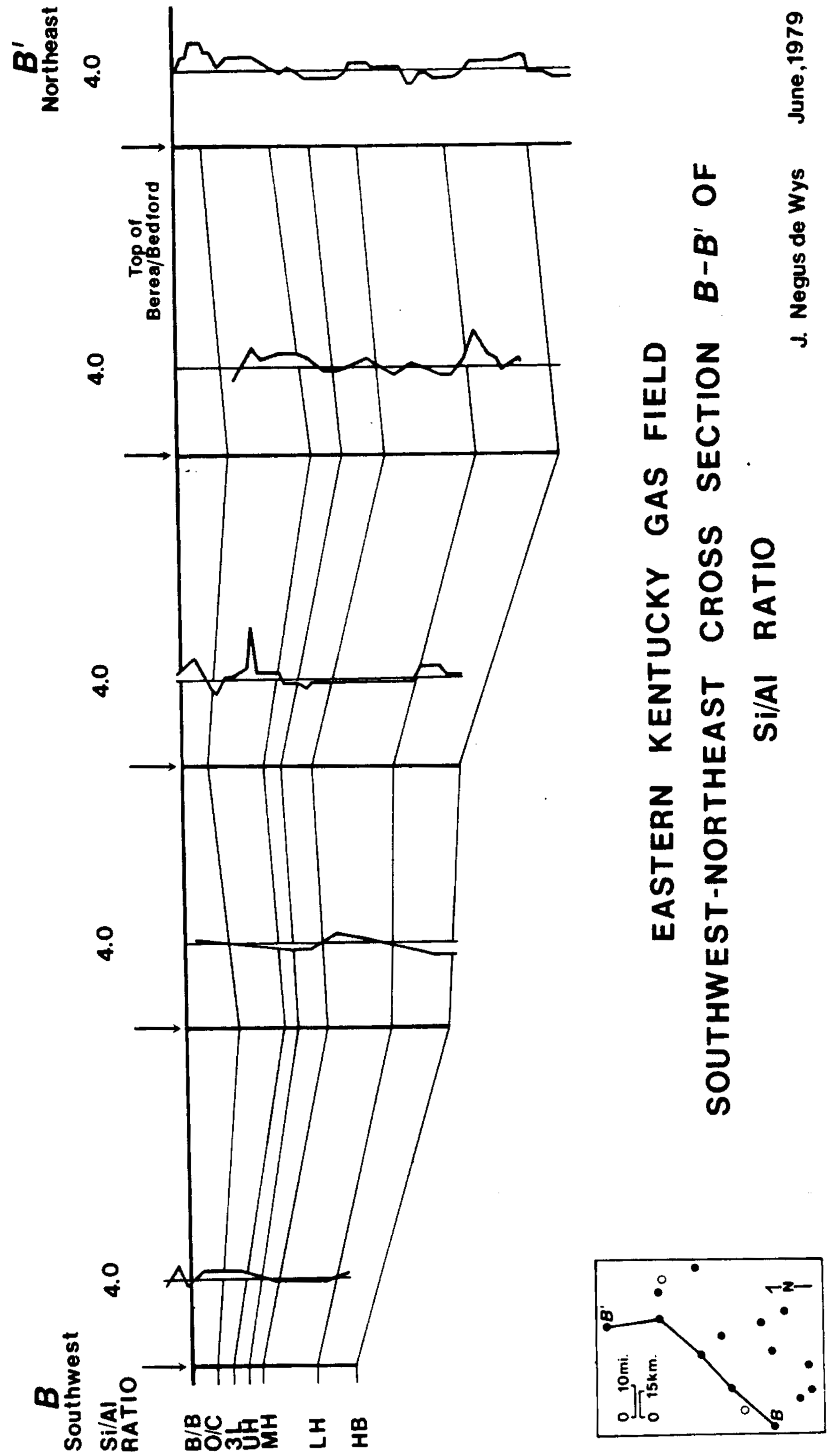

Figure 60. Si/Al oxide ratio cross section B-B'.

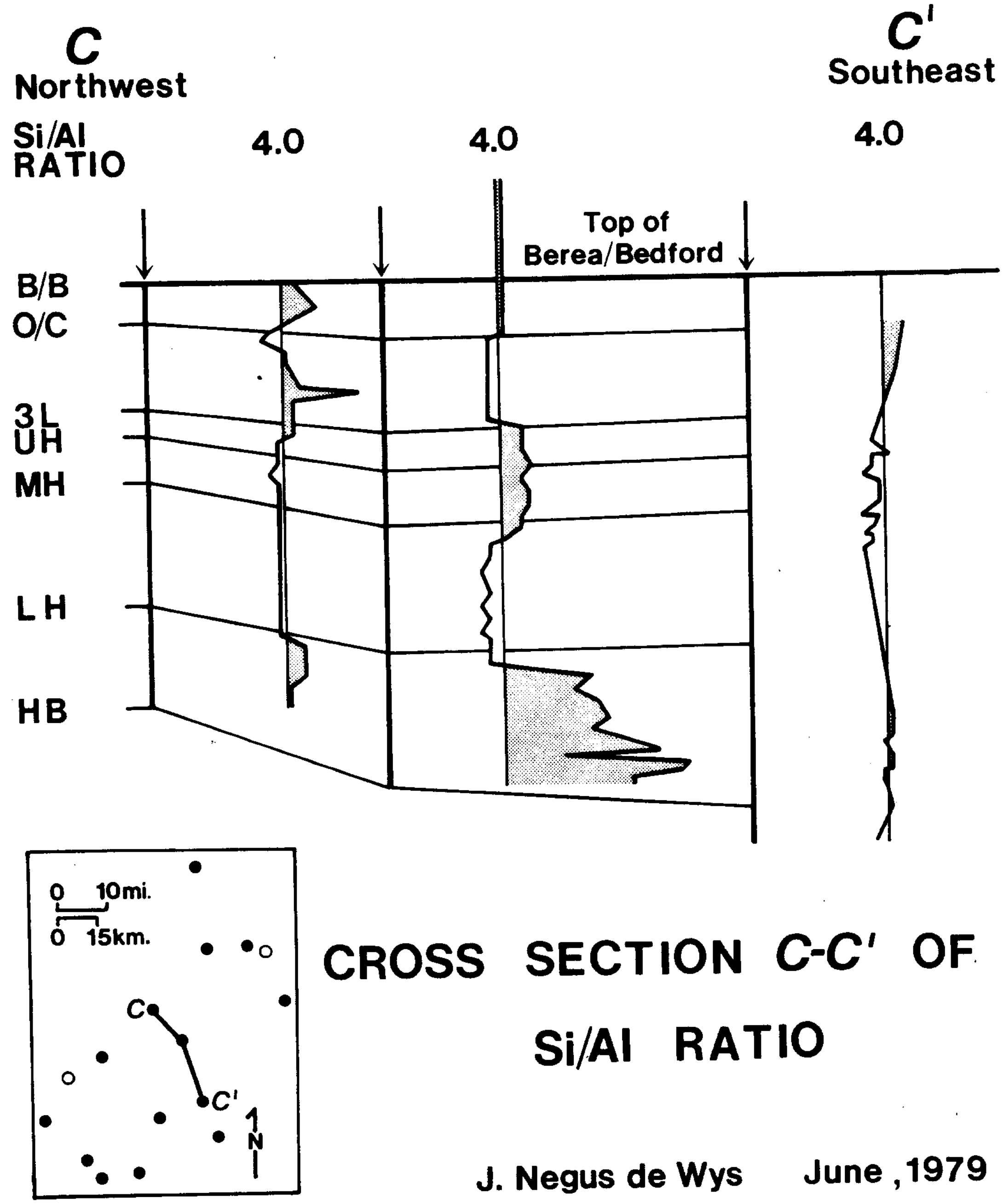

Figure 61. Si/Al oxide ratio cross section C-C'.

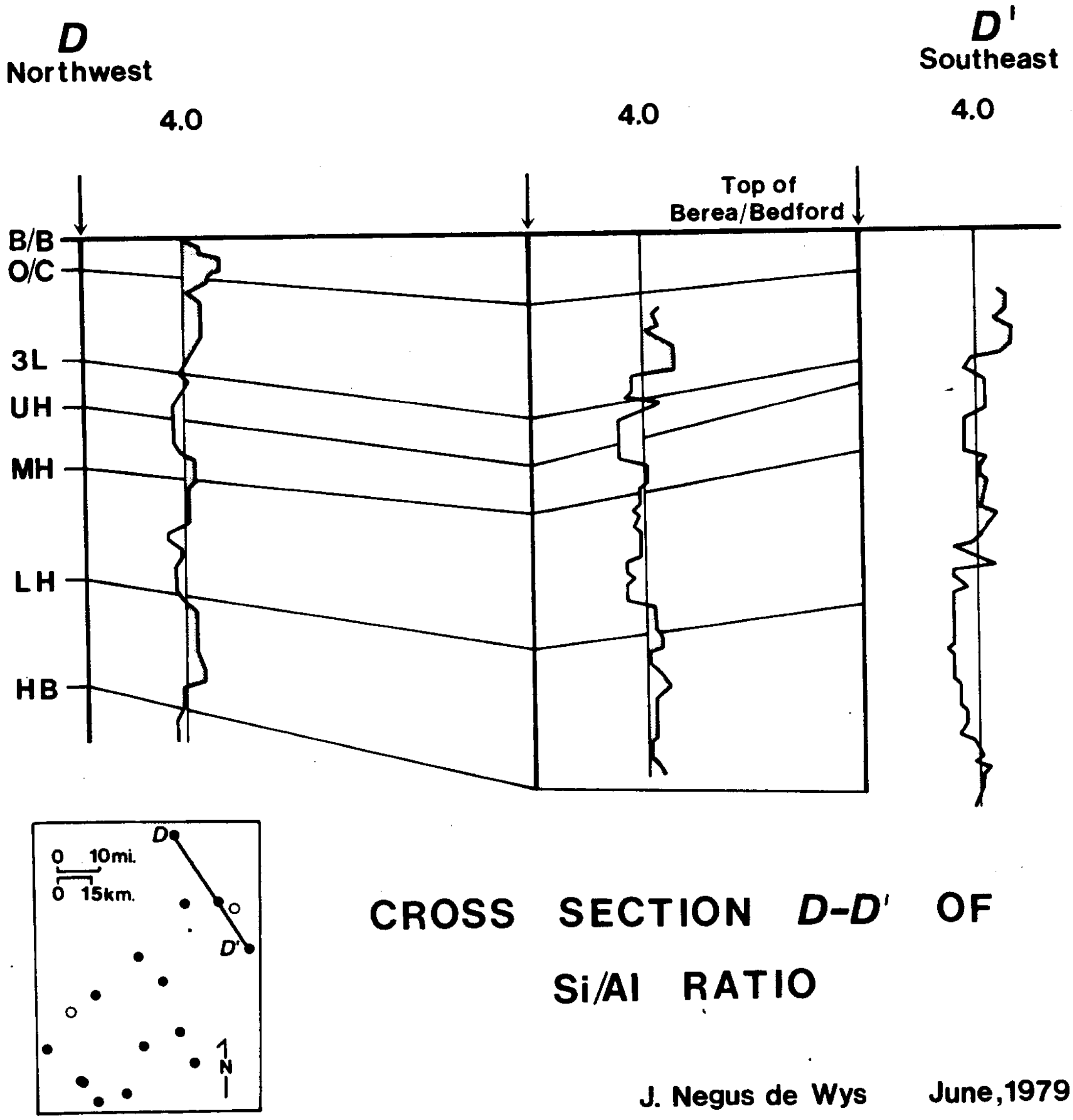

Figure 62. Si/Al oxide ratio cross section D-D'.

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ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	53.20	54.34	54.91	56.06	56.63
MAXIMUM	53.20	54.34	54.91	56.06	56.63	57.20

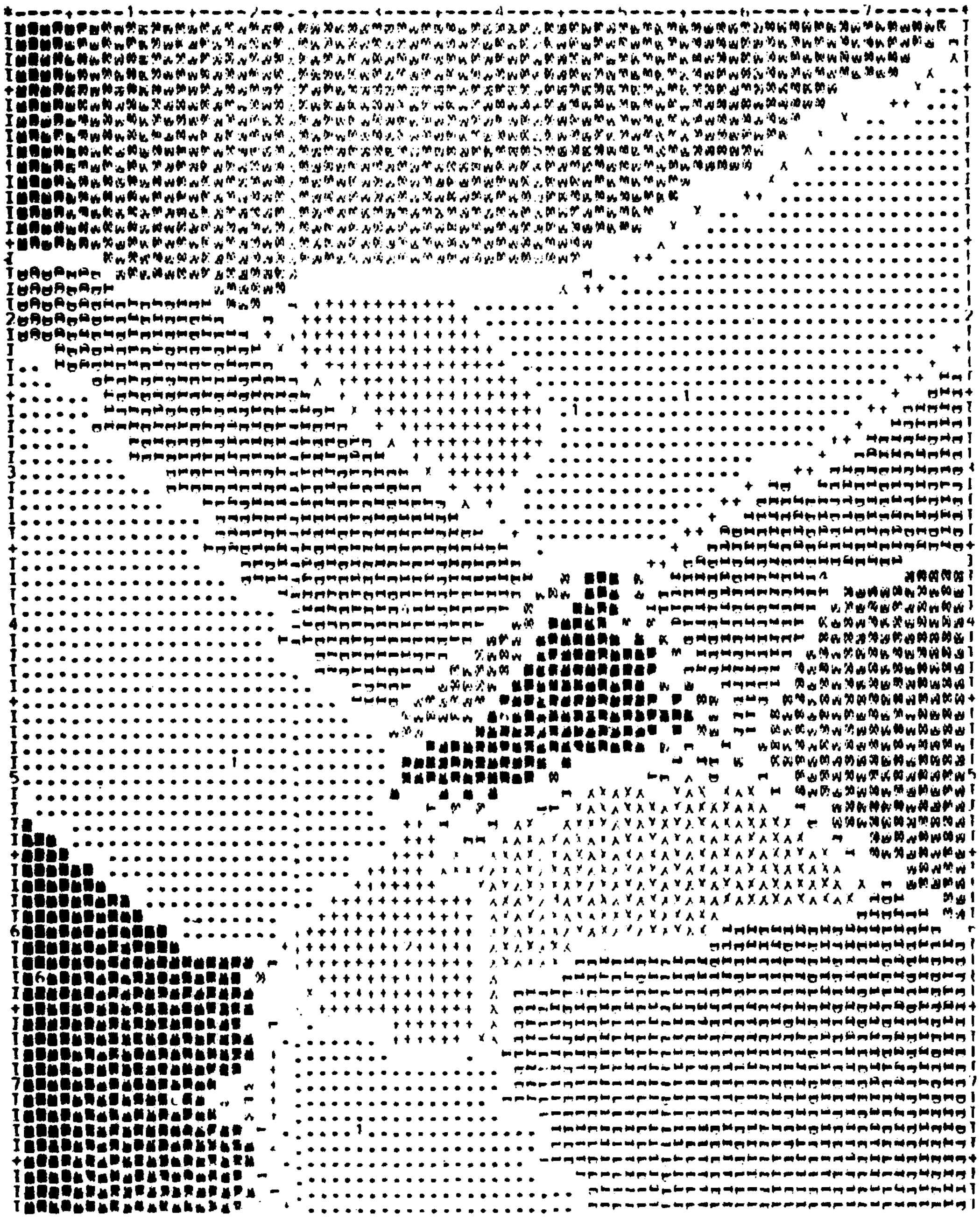
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

93.00	2.00	1.00	2.00	1.00	1.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

```
 LEVEL          1          2          3          4          5          6
            ===========================================================
             .........  +++++++++  XXXXXXXXX  000000000  @@@@@@@@@  ■■■■■■■■■
             .........  +++++++++  XXXXXXXXX  000000000  @@@@@@@@@  ■■■■■■■■■
 SYMBOLS     ....1....  ++++2++++  XXXX3XXXX  0000400000 @@@@5@@@@  ■■■■■■■■■
             .........  +++++++++  XXXXXXXXX  000000000  @@@@@@@@@  ■■■■■■■■■
             .........  +++++++++  XXXXXXXXX  000000000  000000000  000000000
            ===========================================================
 FREQ.          4          2          1          3          1          3
           1  I..1..I    I++2++I    IXX3XXI    I004001    I@@5@@I    I■■6■■I
           2  I..1..I    I++2++I               I004001               I■■6■■I
           3  I..1..I                          I004001               I■■6■■I
           4  I..1..I
```

Key to Figure 63.



PERCENTAGE OF Si OXIDE FOR THE THREE LICK UNIT N

Figure 63. Computer-generated map of average Si oxide values in the Three Lick unit. Darkest print out area represents the highest level. Intervals in mapping are not necessarily equal value increments because of computer mapping constraints. See key on preceeding page.

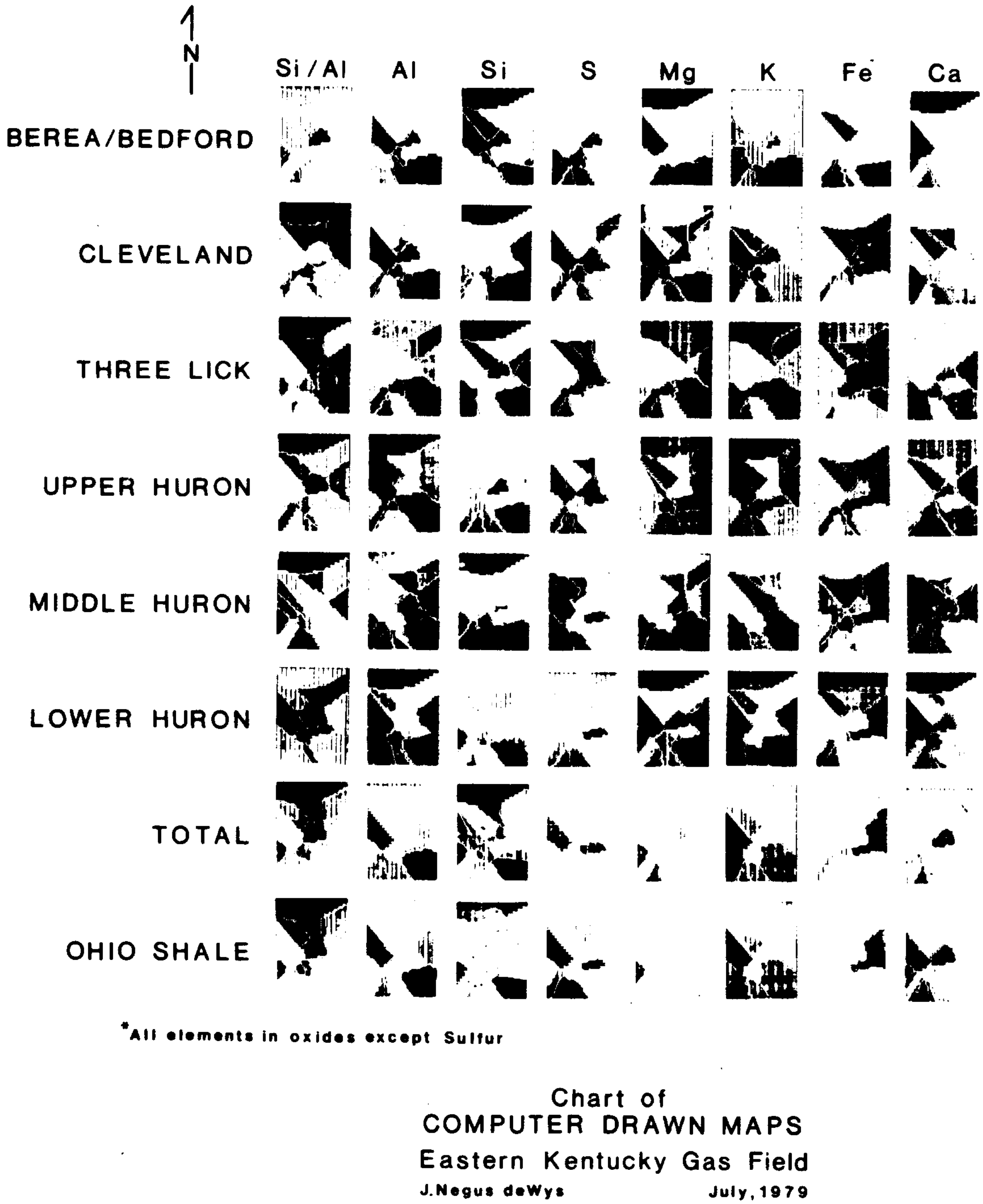


Figure 64. Comparison of computer drawn map miniatures for all units for Si/Al, Al, Si, S, Mg, K, Fe, and Ca.

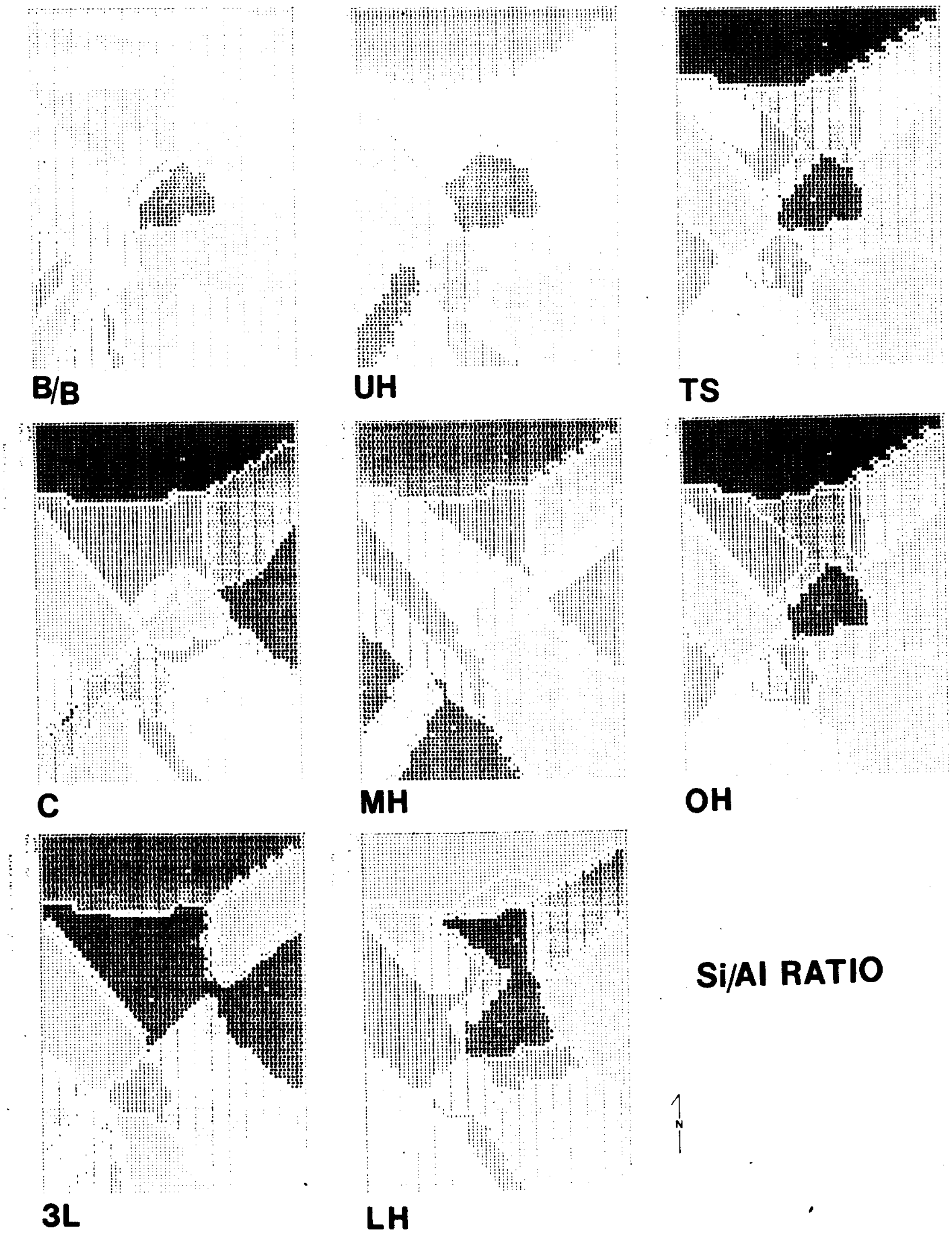


Figure 65. Computer-drawn maps for Si/Al oxide ratio for stratigraphic units. B/B = Berea/Bedford; C = Cleveland; 3L = Three Lick; UH = Upper Huron; MH = Middle Huron; and LH = Lower Huron; TS = Total Shale Sequence; OS = Ohio Shale.

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	0.17	0.40	0.62	0.85	4.58
MAXIMUM	0.17	0.40	0.62	0.85	4.58	4.98

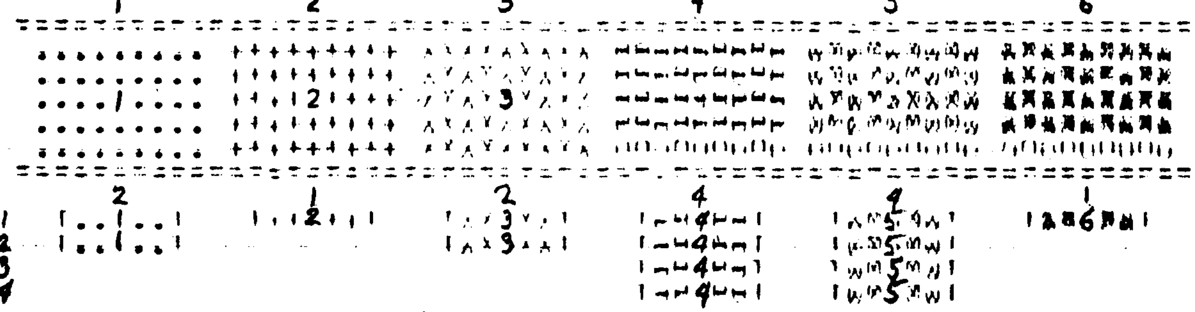
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

3.50	4.50	4.50	4.50	75.00	8.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6
FREQ.	2	1	2	4	4	1

SYMBOLS



1 2 3 4

TIME = 0.0

Key to Figure 66.

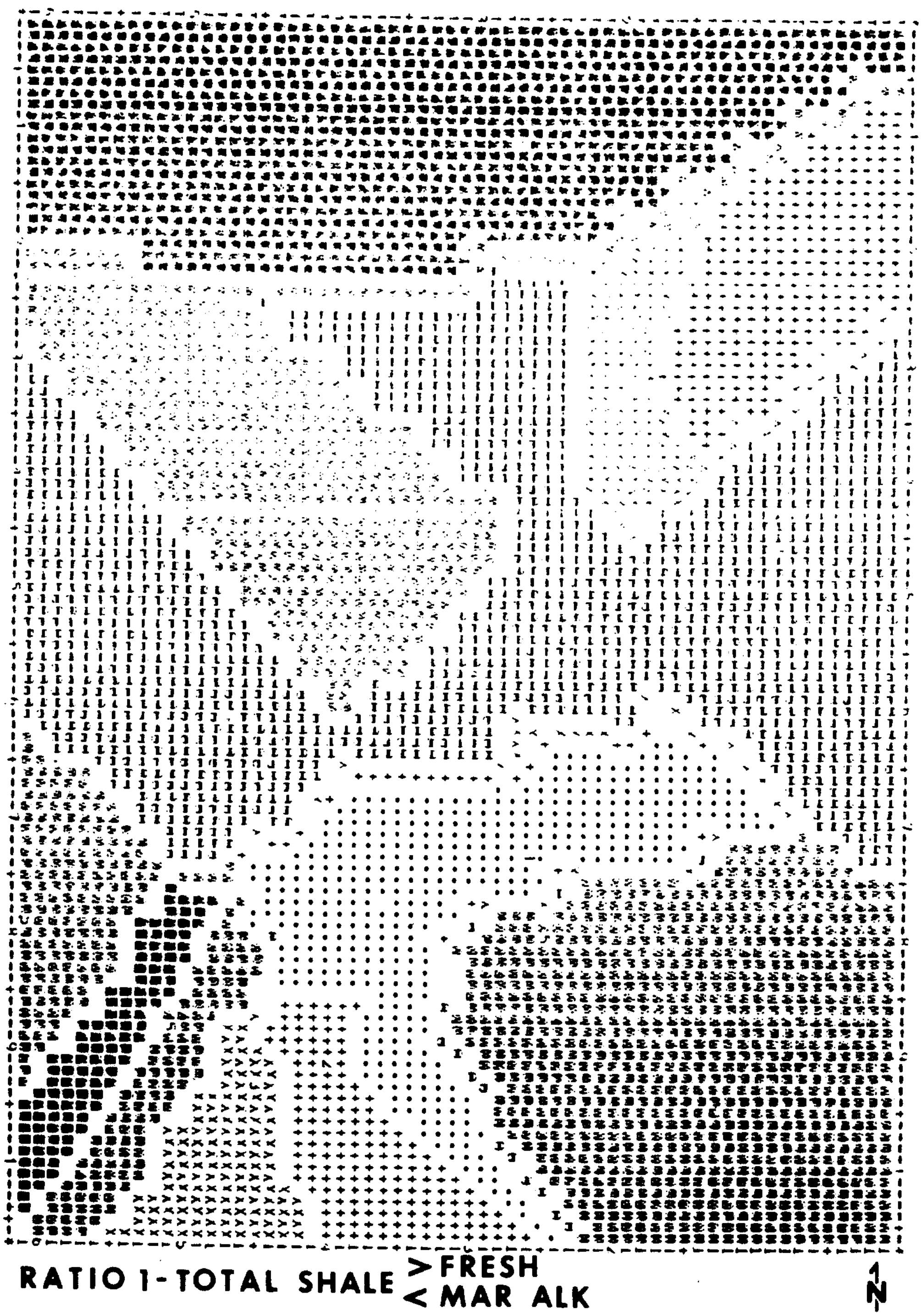


Figure 66. Computer-drawn map of Ratio 1 for total stratigraphic sequence studied.

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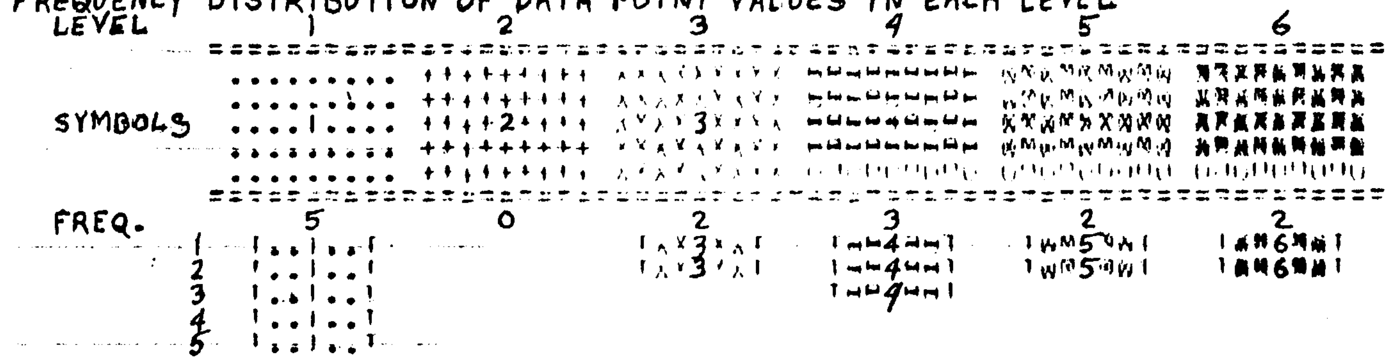
ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	33.32	35.21	37.09	38.98	40.87	42.75
MAXIMUM	35.21	37.09	38.98	40.87	42.75	44.64

PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

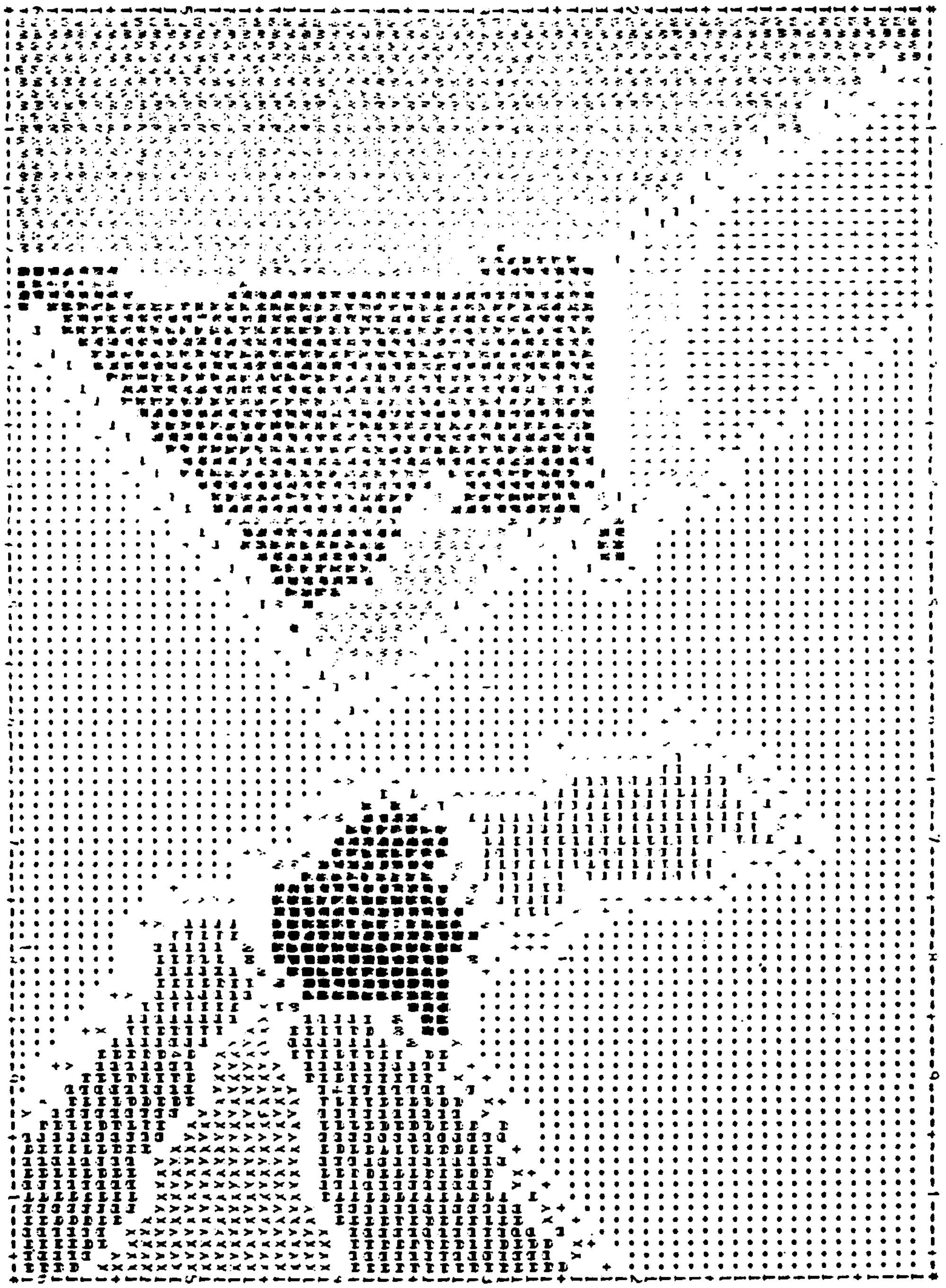
16.67	16.67	16.67	16.67	16.67	16.67

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL



TIME = 0.0

Key to Figure 67.



RATIO 2 > CLOSER TO CLASTIC SOURCE

Figure 67. Computer-drawn map of Ratio 2 for total stratigraphic sequence studied.

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	9.10	17.58	60.00	76.97	82.91	88.85
MAXIMUM	17.58	60.00	76.97	82.91	88.85	93.94

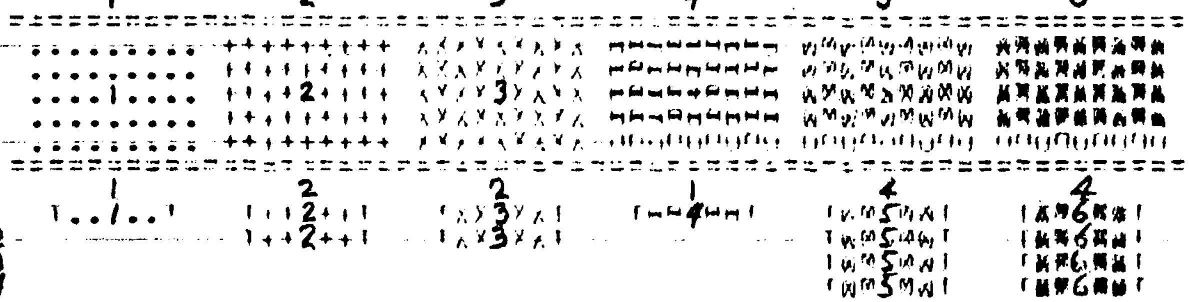
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

10.00	50.00	20.00	7.00	7.00	6.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6

SYMBOLS



FREQ.	1	2	2	1	4	4

TIME = 0.0

Key to Figure 68.

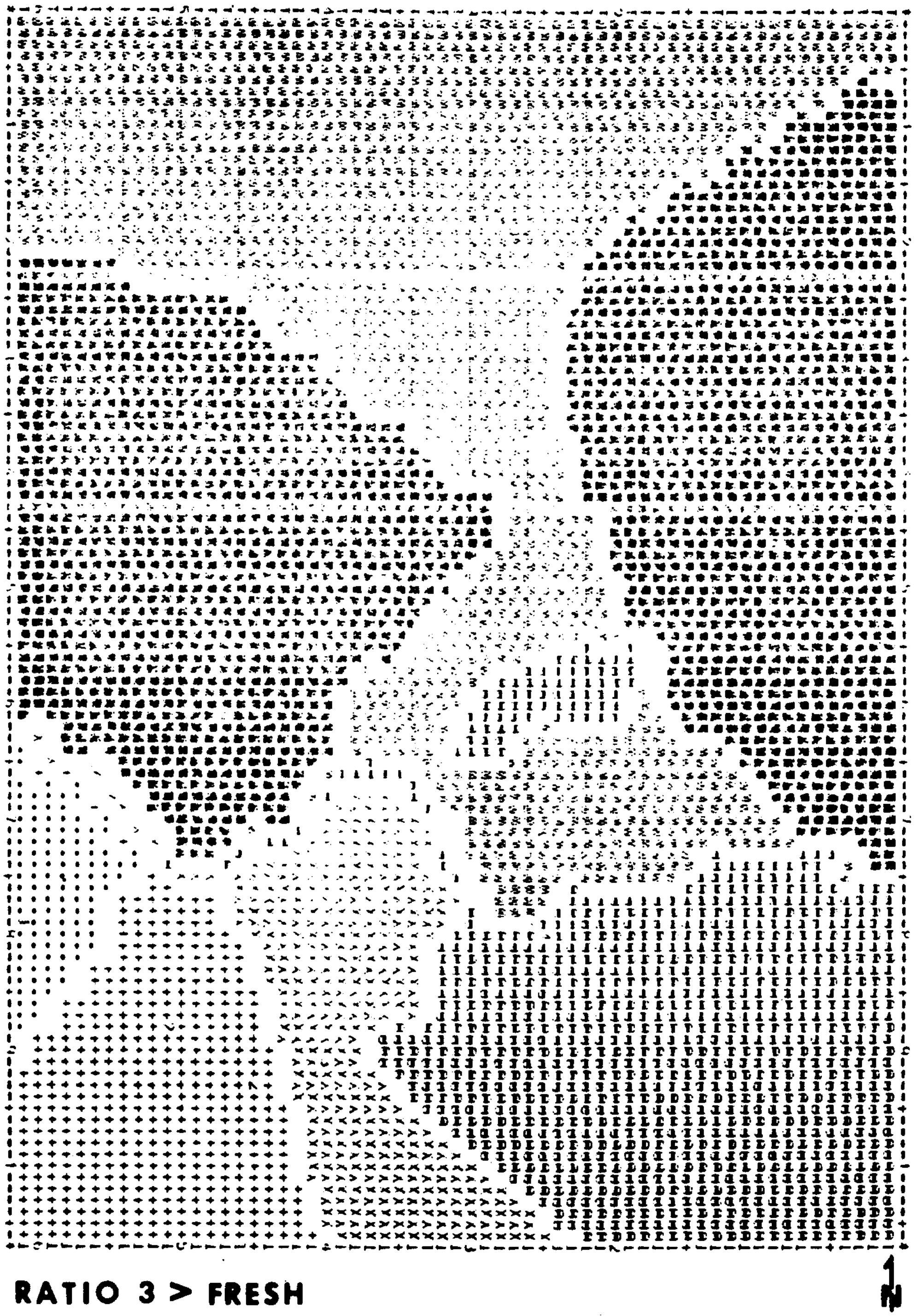


Figure 68. Computer-drawn map of Ratio 3 for total stratigraphic sequence studied.

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	0.32	1.60	6.38	19.15	28.73
MAXIMUM	0.32	1.60	6.38	19.15	28.73	31.92

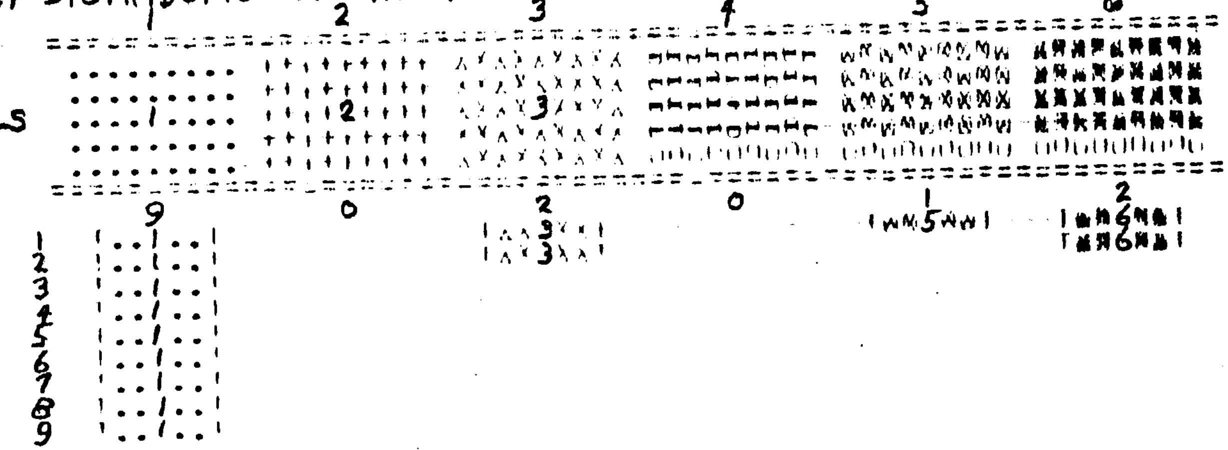
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

1.00	4.00	15.00	40.00	30.00	10.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

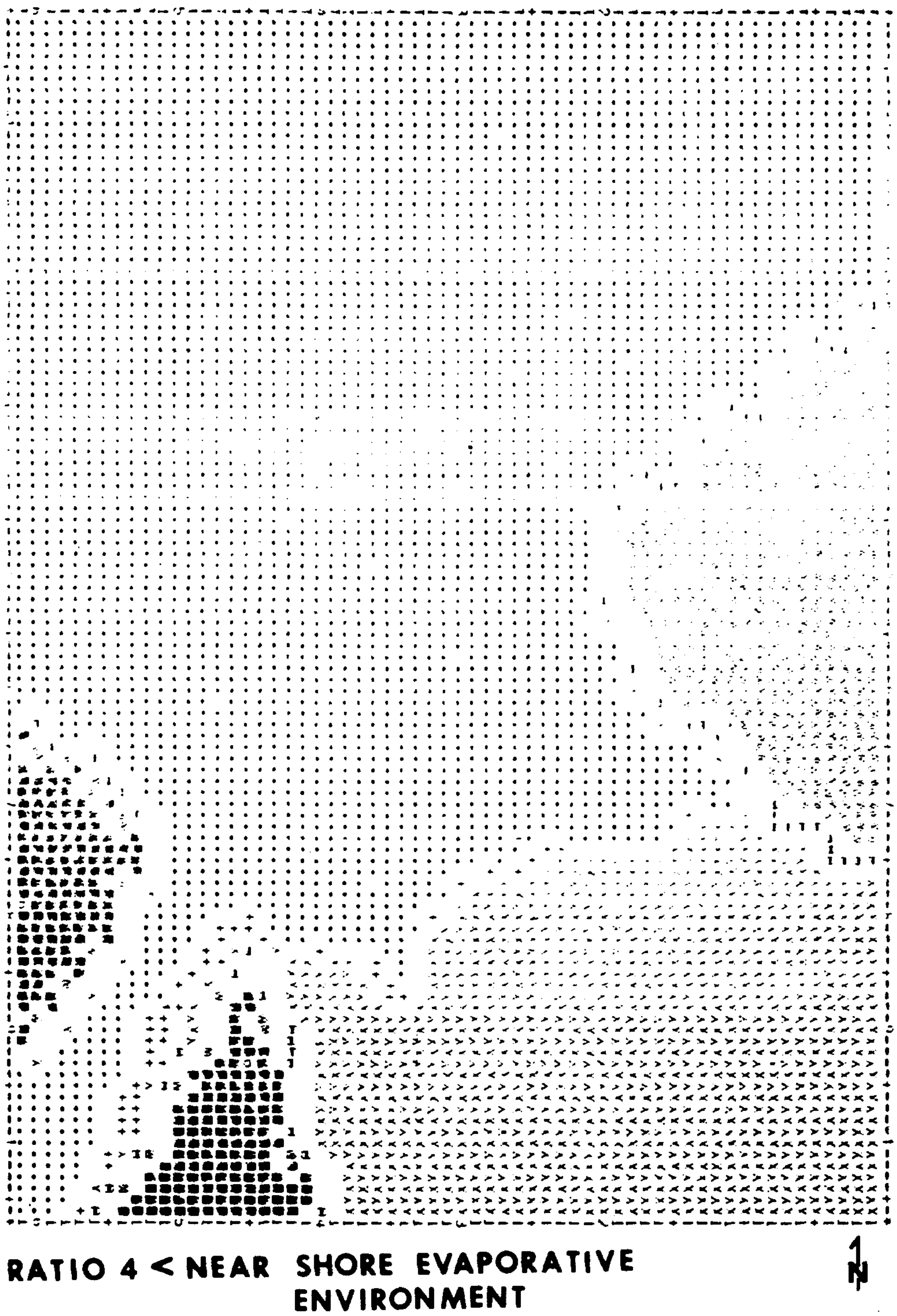
FREQUENCY LEVEL	1	2	3	4	5	6
FREQ.	9	0	2	0	1	2

SYMBOLS



TIME = 0.0

Key to Figure 69.



<u>Figure 69</u>. Computer-drawn map of Ratio 4 for total stratigraphic sequence studied.

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	77.82	82.26	90.02	91.57	93.12	95.56
MAXIMUM	82.26	90.02	91.57	93.12	95.56	100.00

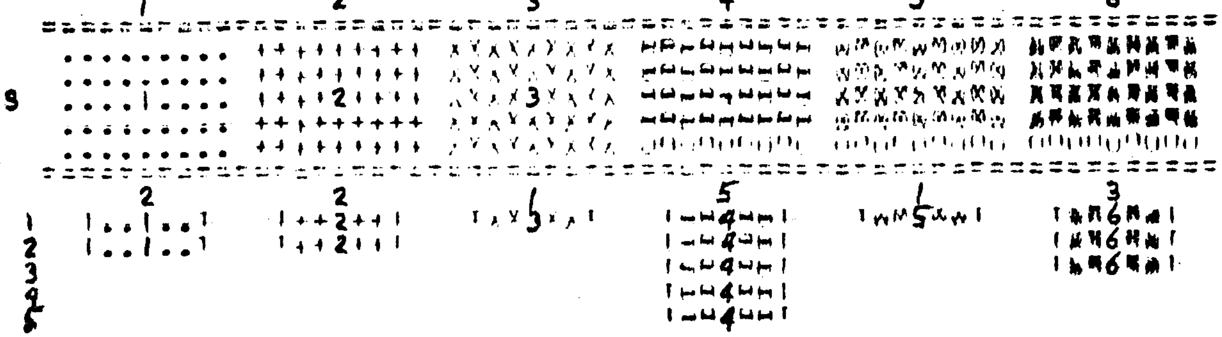
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL

20.00	35.00	7.00	7.00	11.00	20.00

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

LEVEL	1	2	3	4	5	6
FREQ.	2	2	1	5	1	3

SYMBOLS



TIME = 0.0

Key to Figure 70.

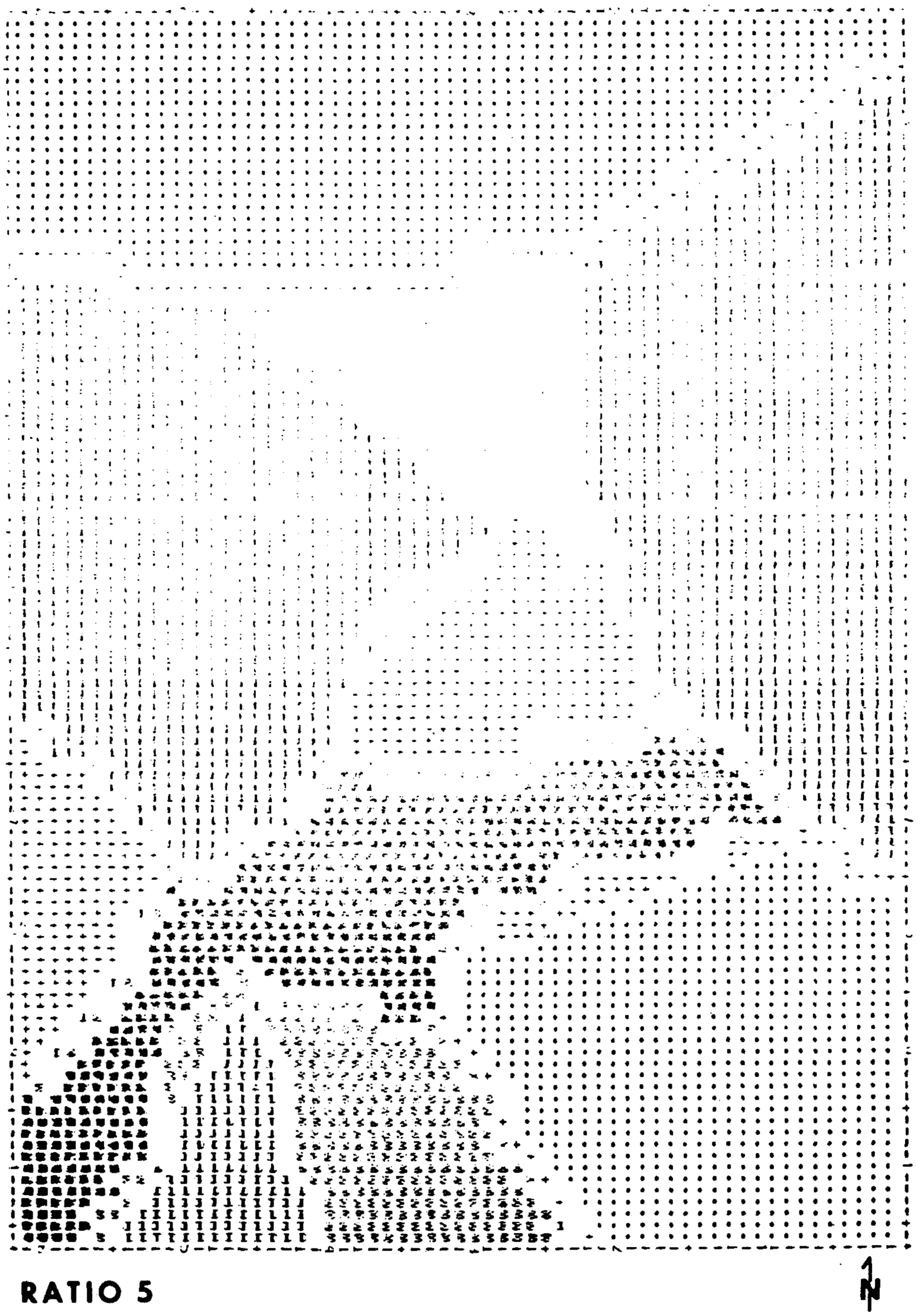


Figure 70. Computer-drawn map of Ratio 5 for total stratigraphic sequence studied.

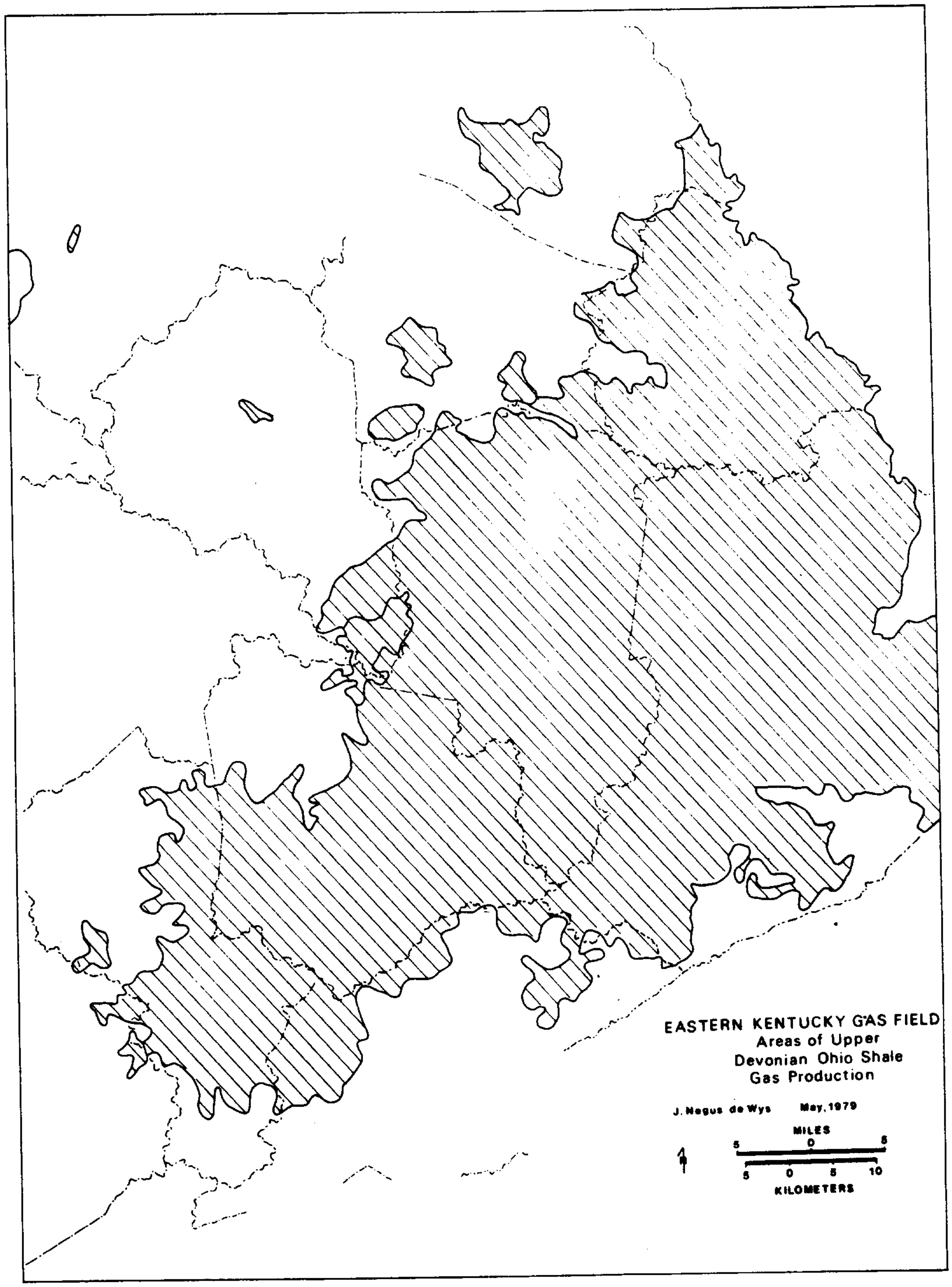


Figure 71. Areas of Upper Devonian Ohio Shale gas production.

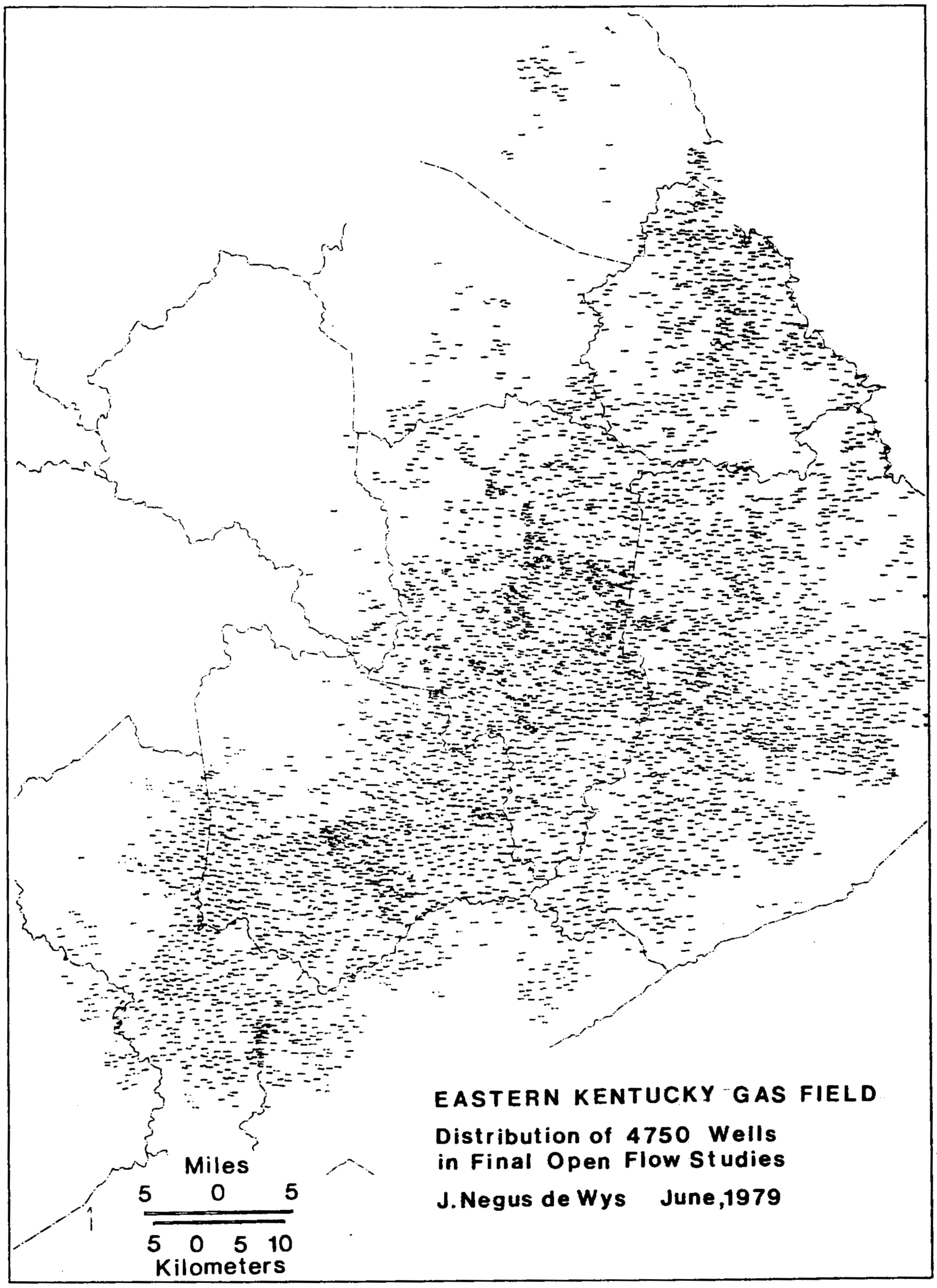


Figure 72. Locations of 4750 wells for which final open flow data was supplied by Kentucky-West Virginia Gas.

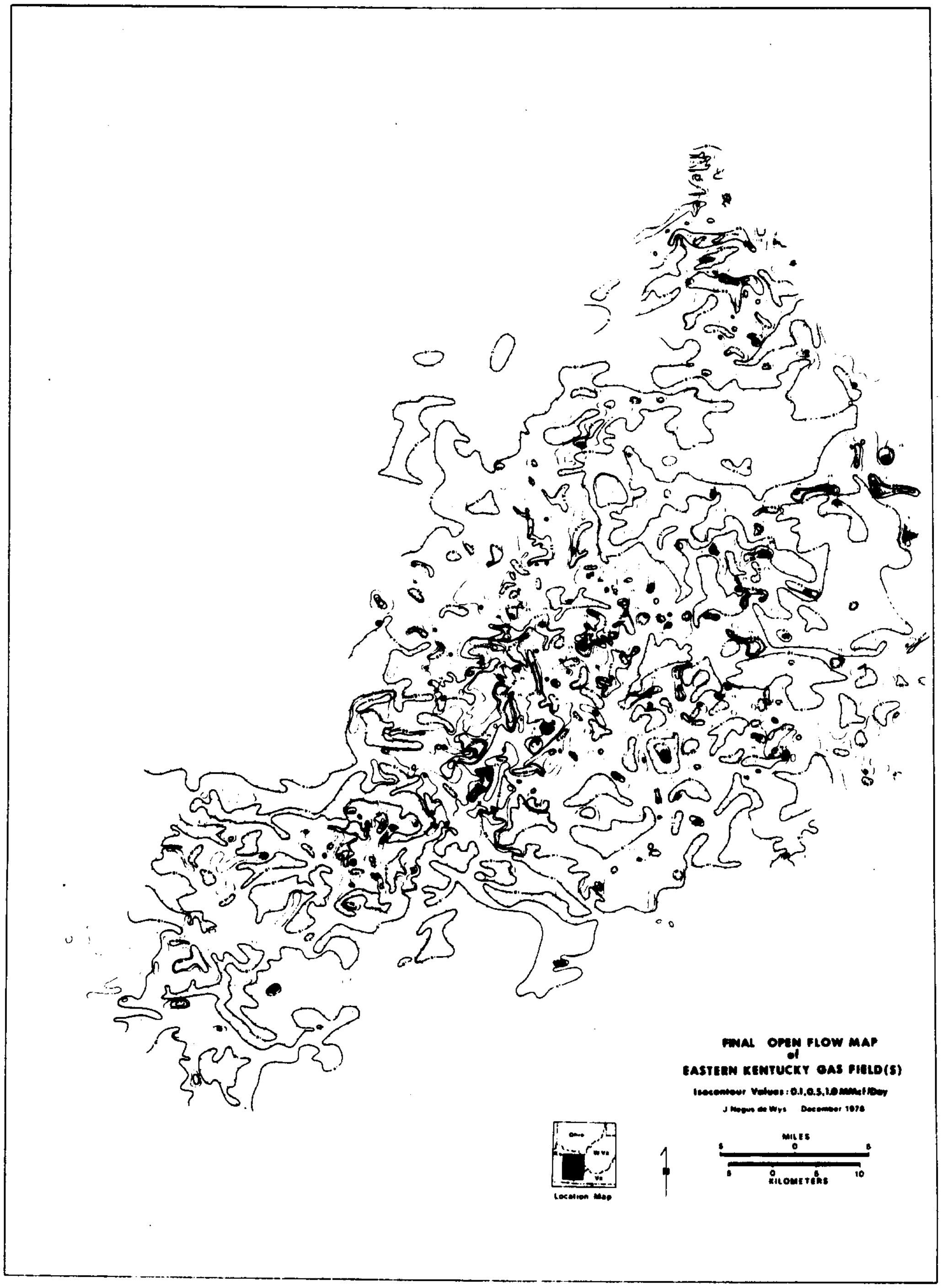


Figure 73. Hand-contoured map of final open flow data from 4750 wells. Complexity of the coalesced fields is apparent.

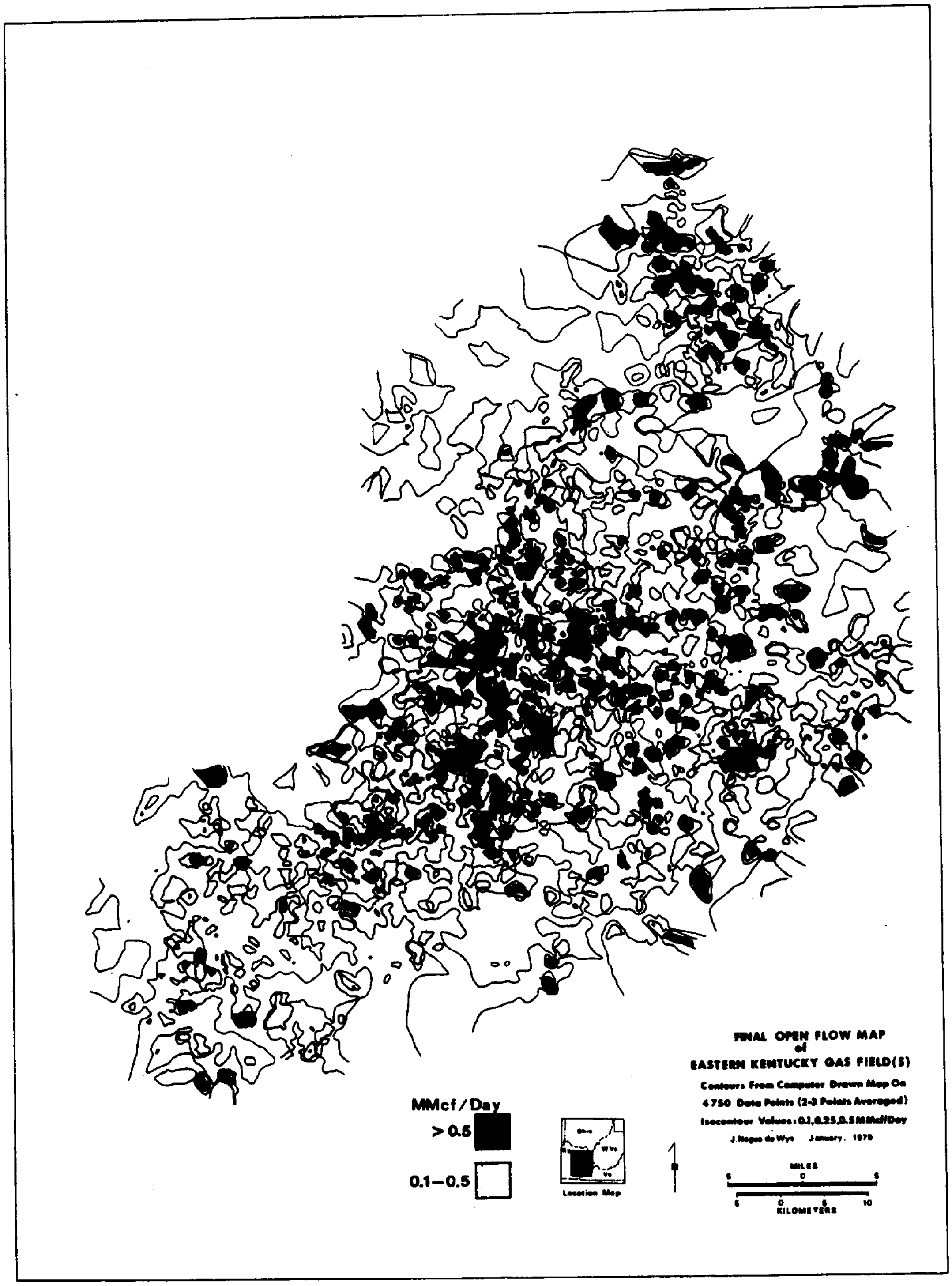


Figure 74. Computer-drawn map of open flow data.

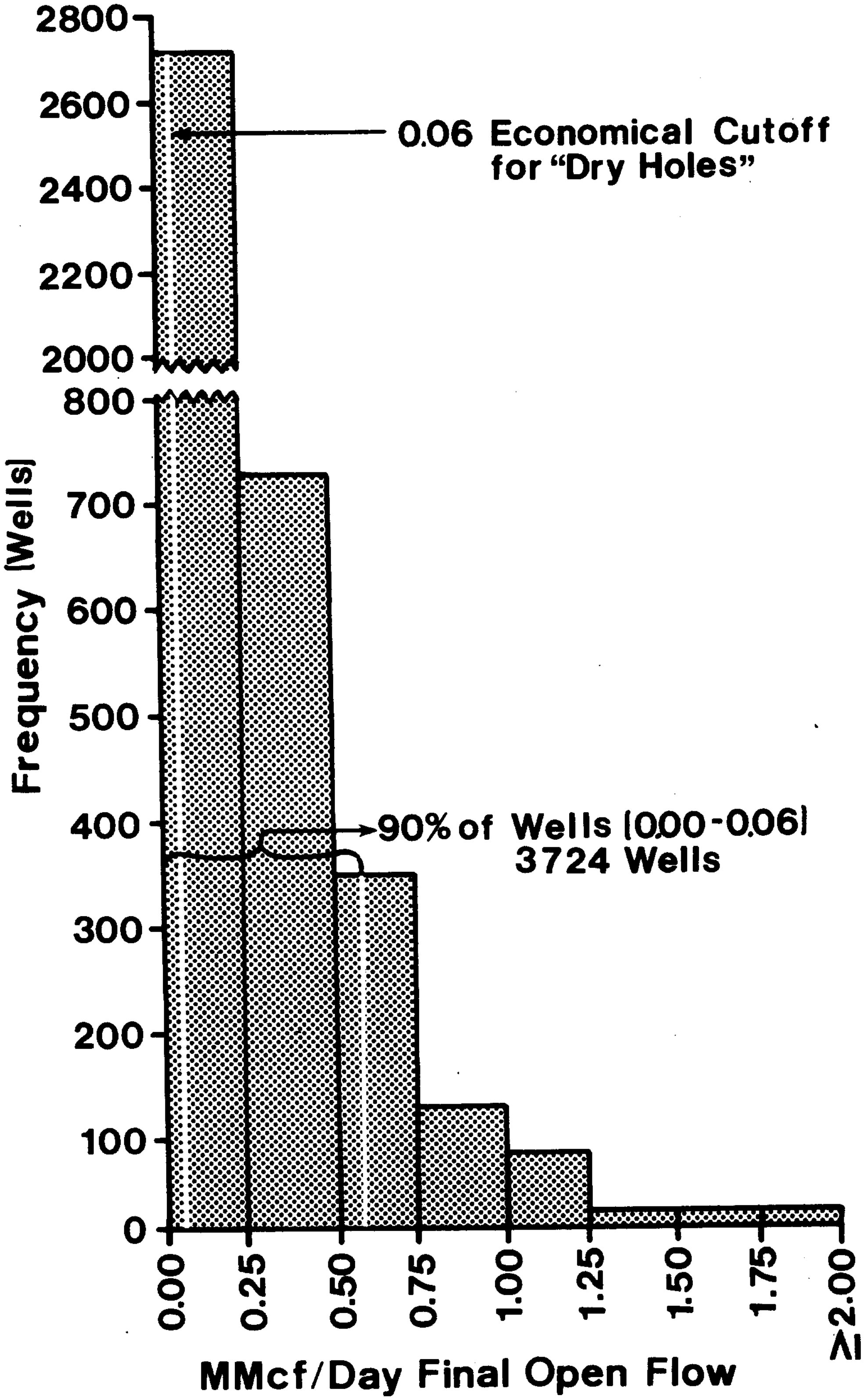


Figure 75. Histogram of open flow data (0.00 ≥ 2.00 MMcf/day open flow). Vertical scale is number of wells. Total wells = 4750; total wells used = 4138. Note vertical break in scale.

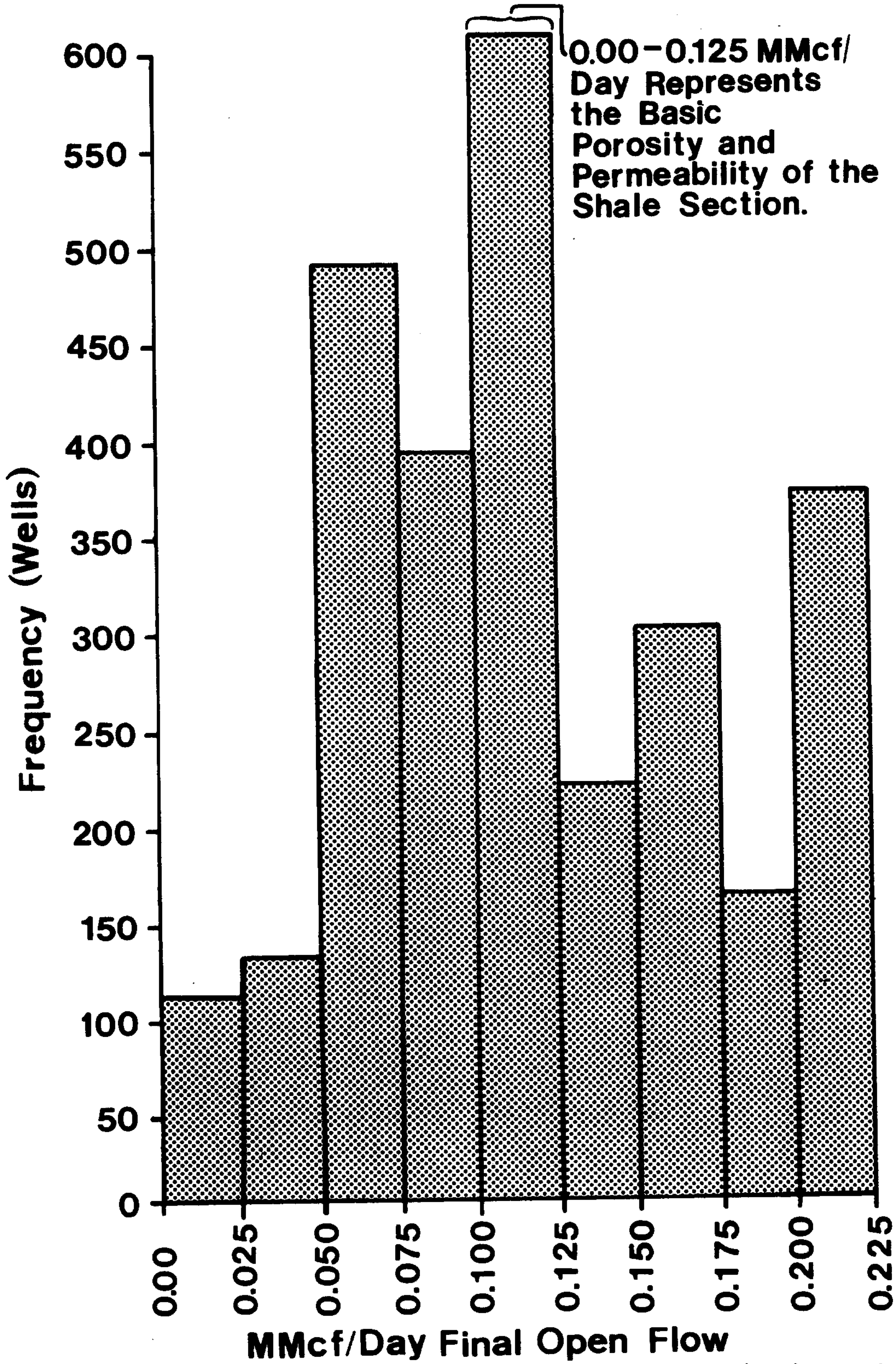


Figure 76. Histogram of open flow data (0.00-0.225 MMcf/day) vertical scale is number of wells.

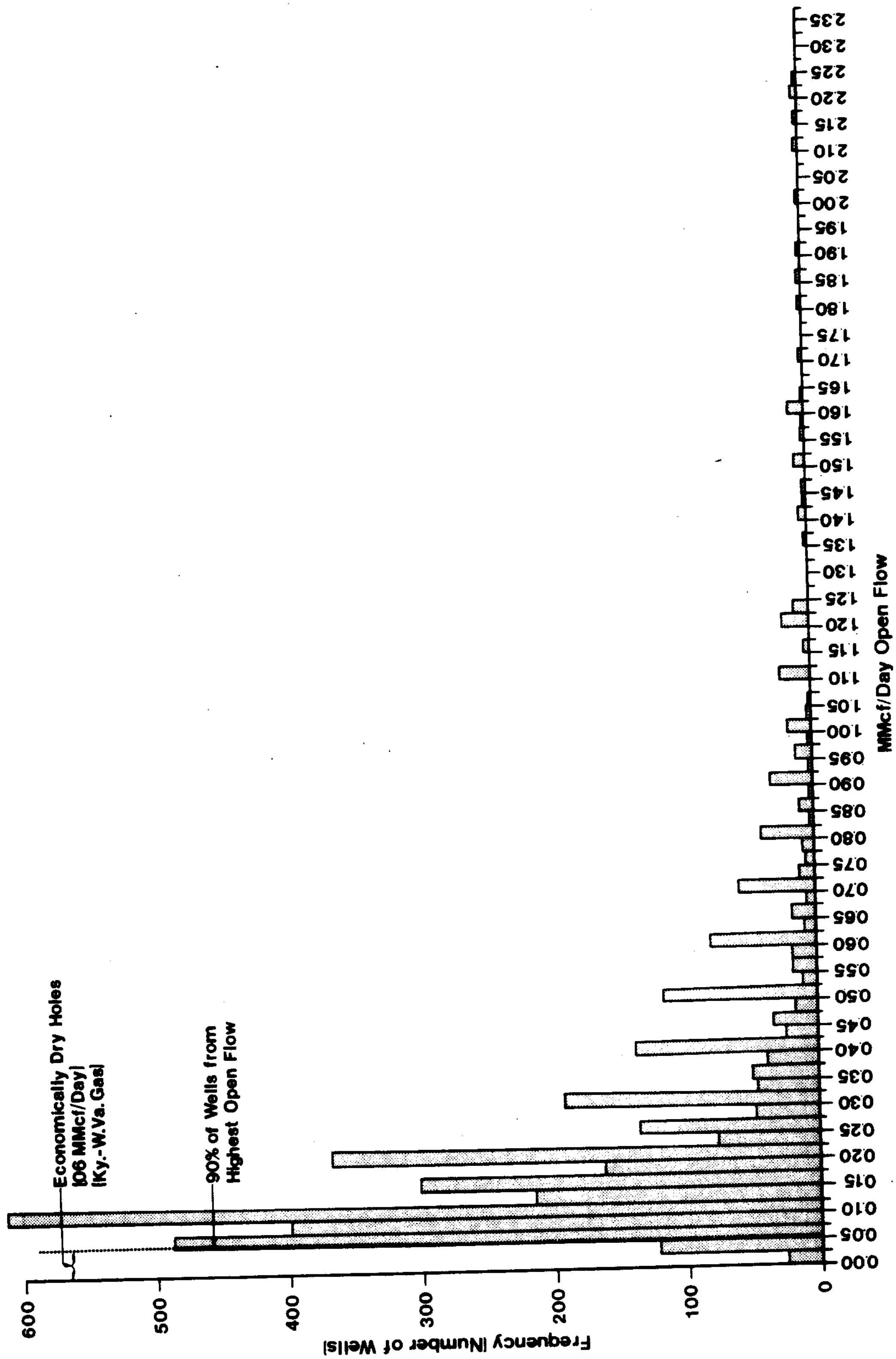


Figure 77a. Histogram of all wells used in computer-mapping (4138). Figure 77b shows tail of histogram representing only 19 wells.

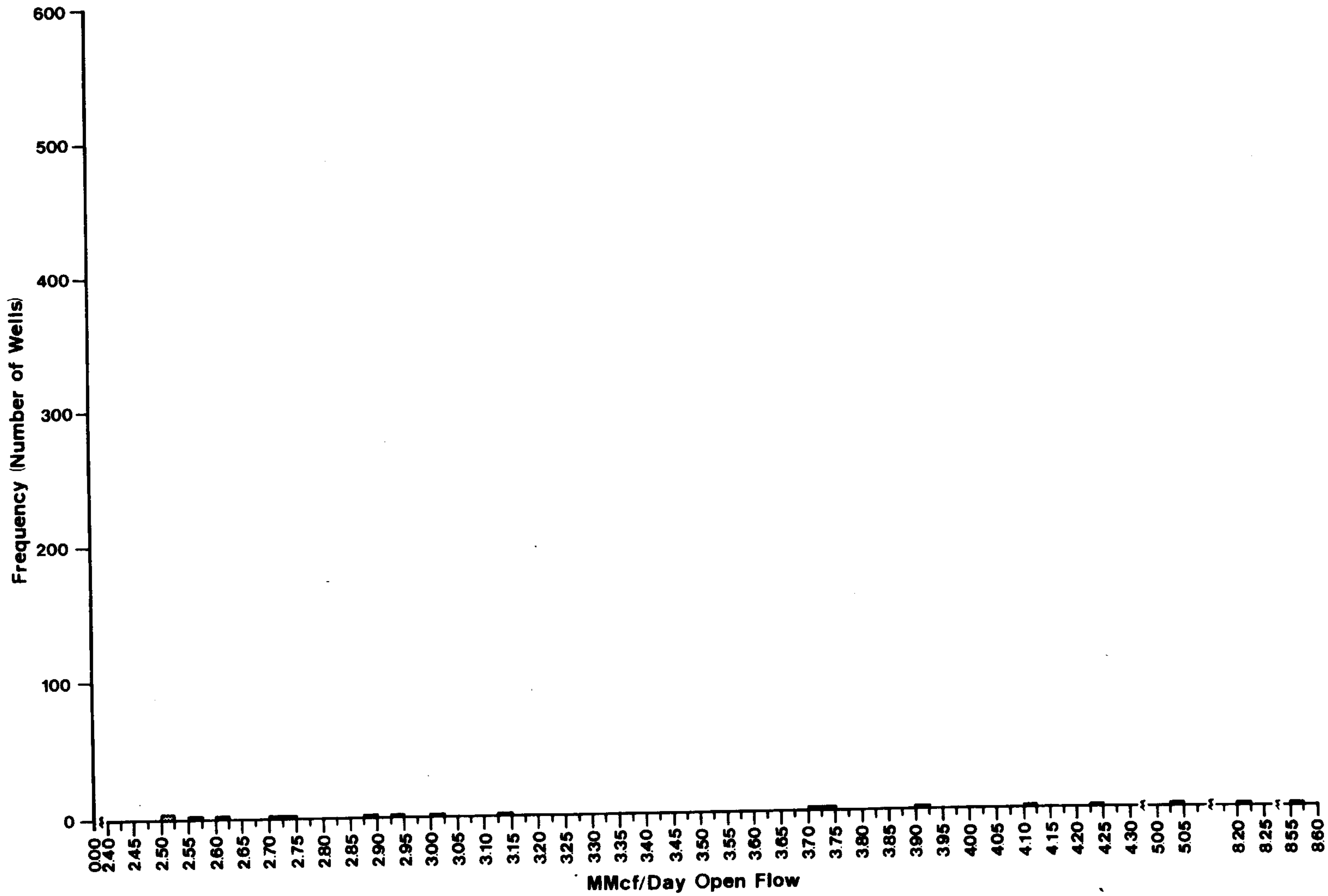


Figure 77b. Histogram tail of 77a, showing highest value 19 wells. Note histogram must be broken twice on the horizontal scale.

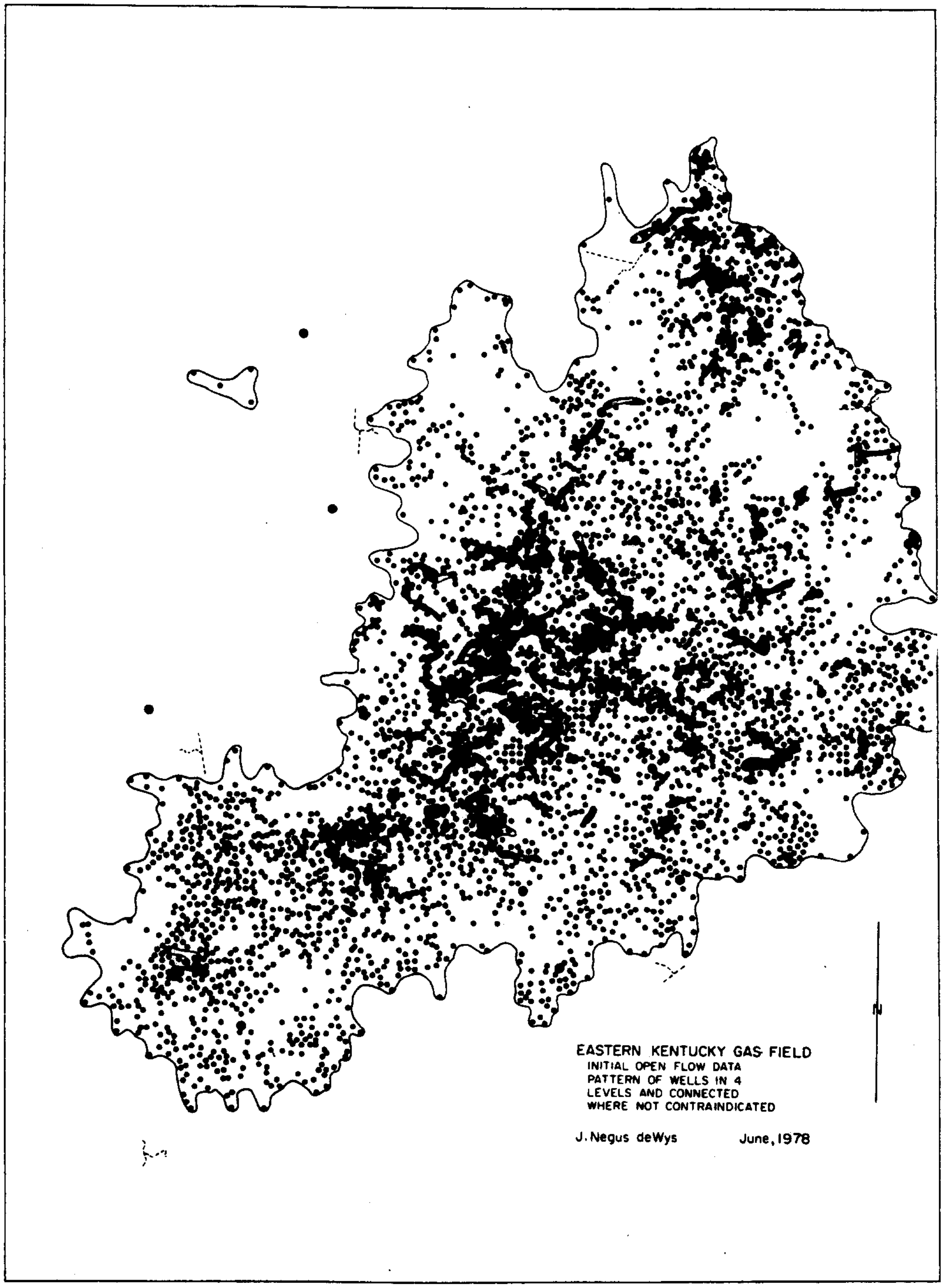


Figure 78. Data points used by Griffith (1976). Points $\geq$ .5 MMcf/day are connected where not contra indicated.

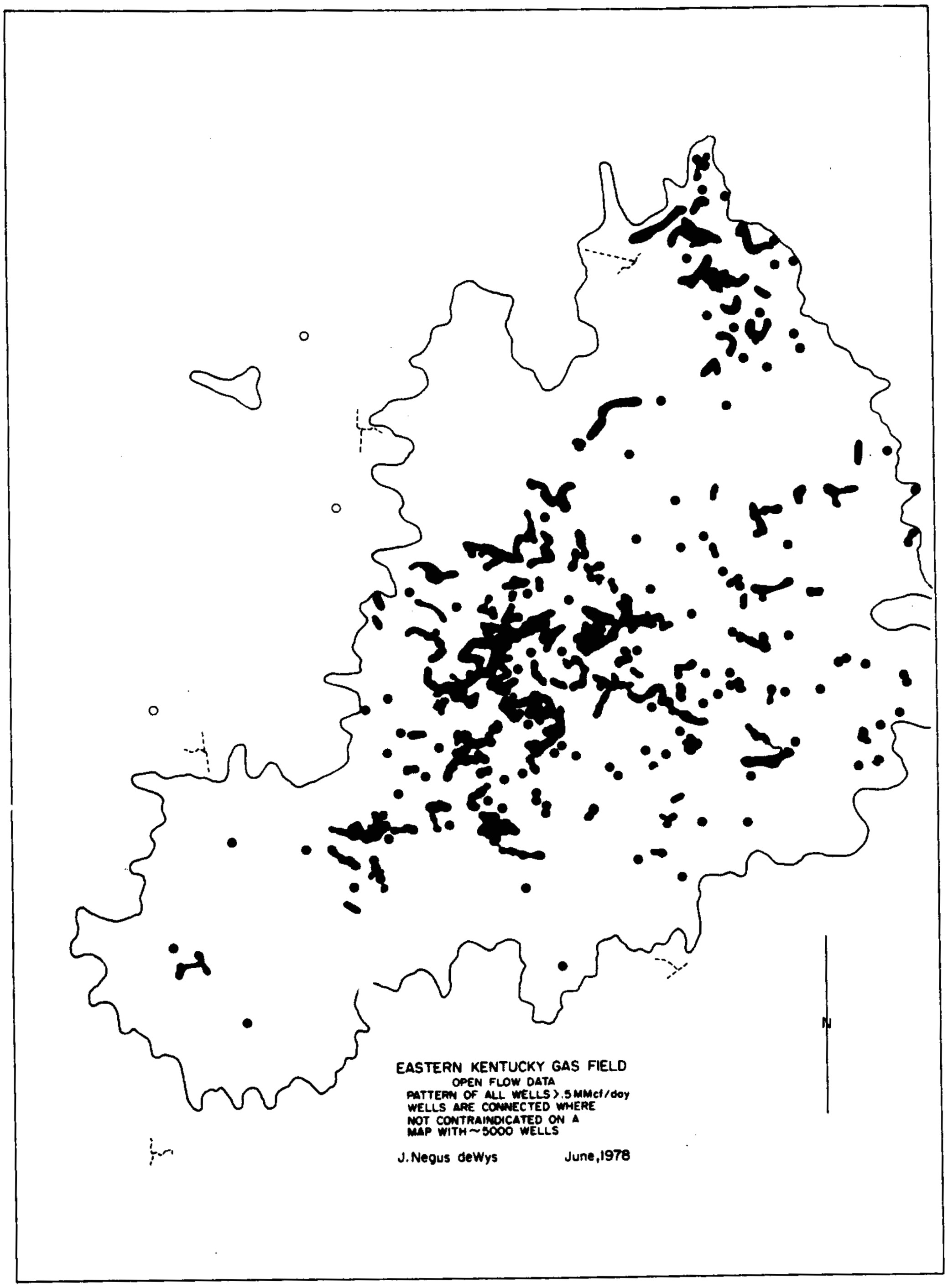
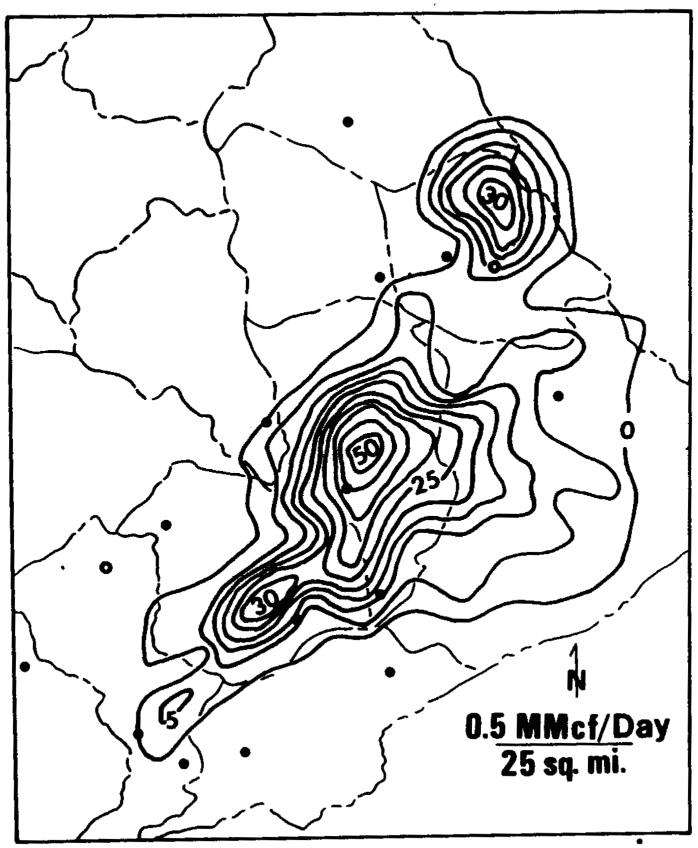
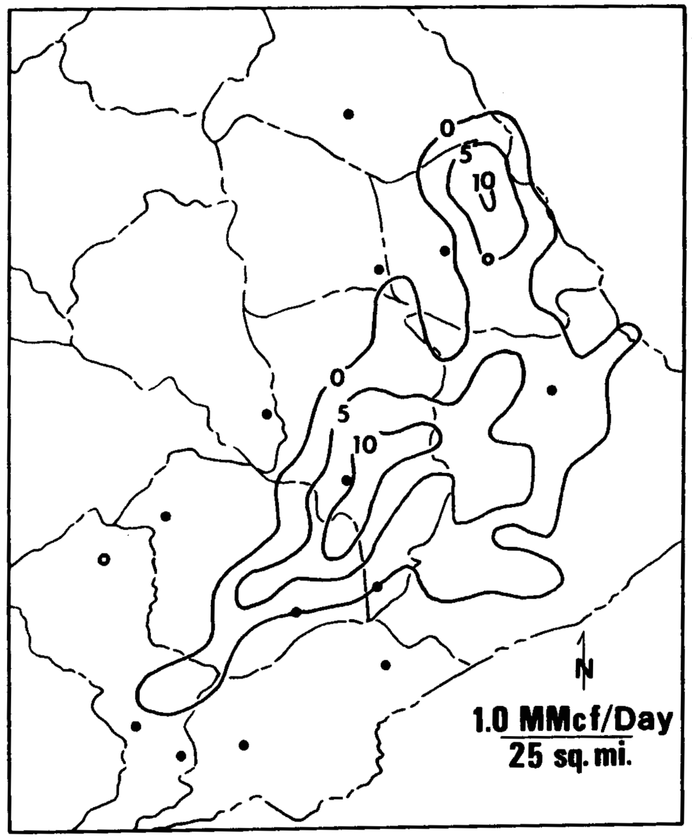


Figure 79. Pattern resulting from connecting all wells with ≥ .5 MMcf/day where not contra indicated. This should be compared with Figure 76 in order to recognize the density of data and constraints of such density imposed on this pattern.



Contours of High Volume Wells
Based on ~4750 Wells
(after Griffith, 1976)



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March, 1979

Figure 80.

Contours of density of high producing wells (after Griffith, 1976). Contours represent number of wells $\geq$ .5 MMcf/day/25 square miles (left) and $\geq$ 1 MMcf/day/25 square miles (right). These figures may be interpreted as the area of gas accumulation with recovery details smoothed out. Note pattern irregularities suggesting linear peripheral extensions. Compare with Figures 77a and 77b.

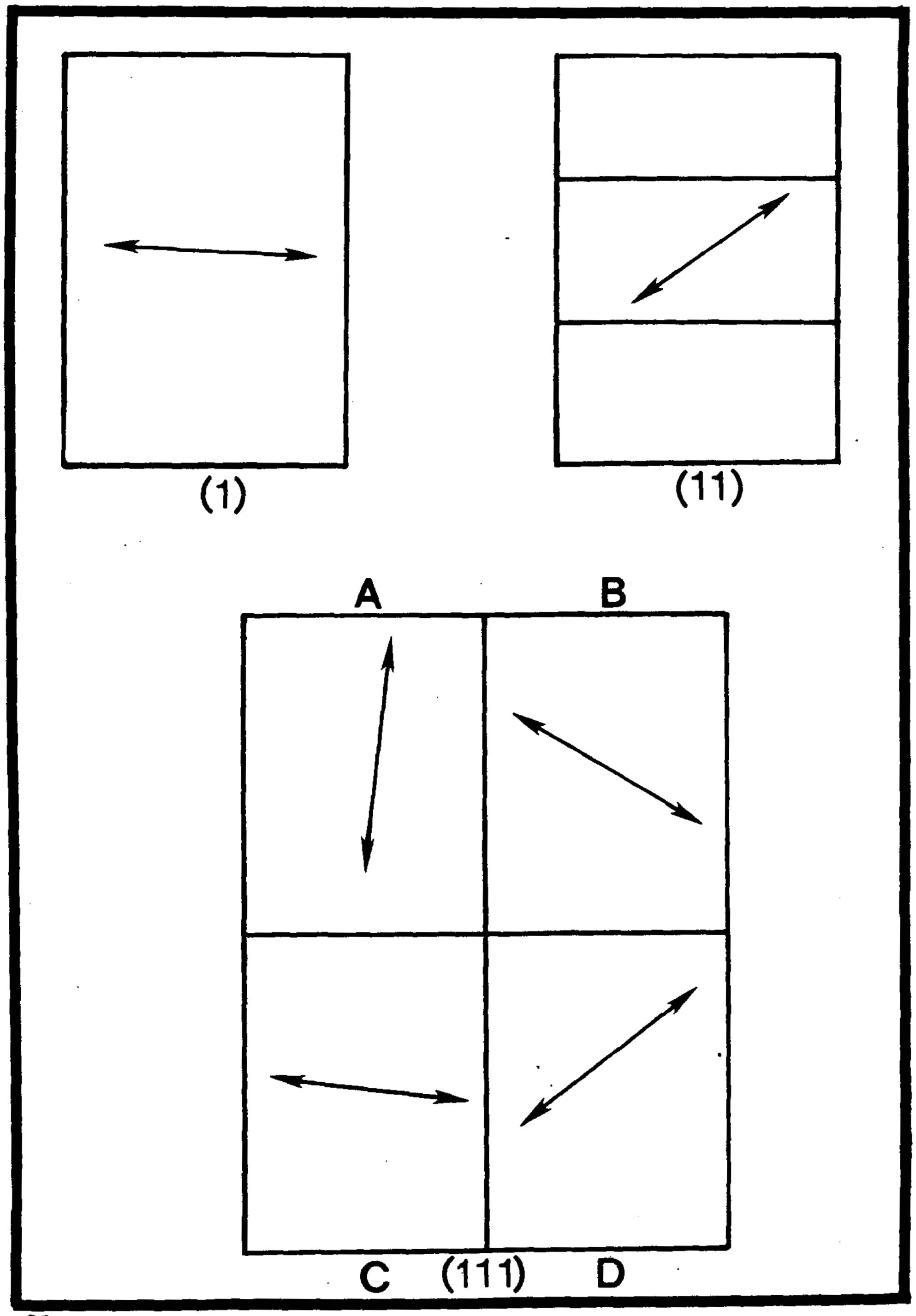
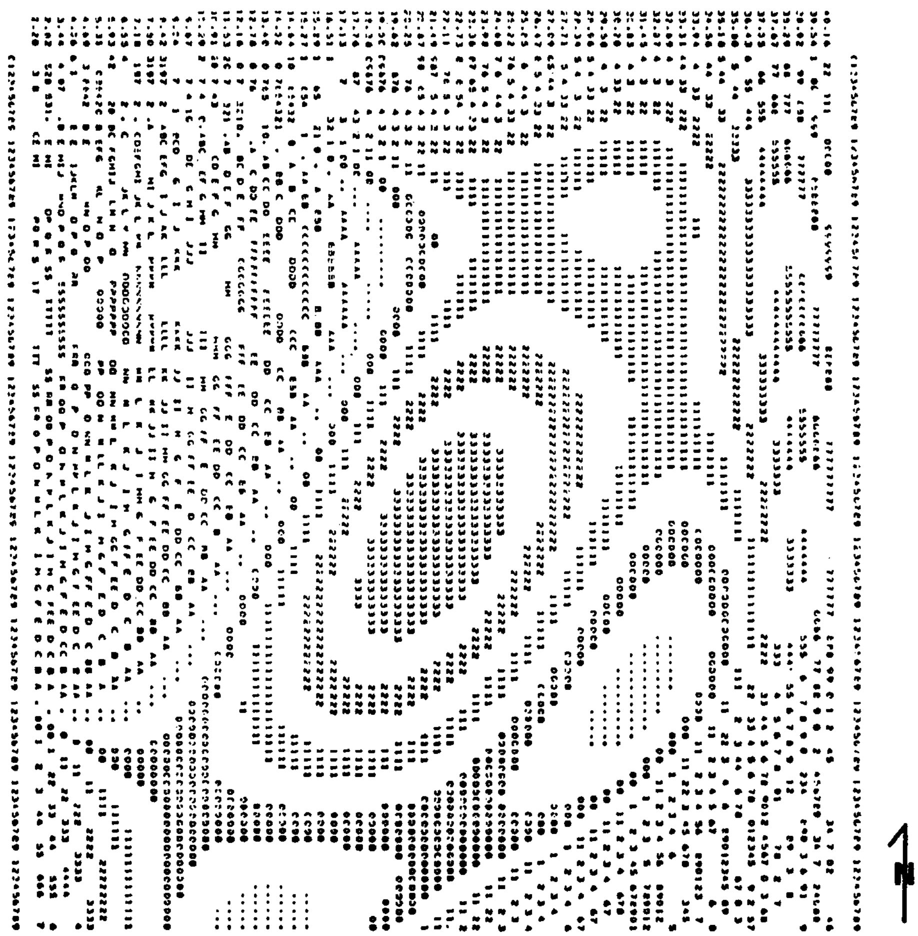


Figure 81.

First degree trends from three trend surface analysis programs. Total map study area is represented by quadrangle in 1, 11, and 111. Areas with arrows are the map segments on which trend surface analysis programs were run. Arrows indicate 1st degree surface, or major trend of data. R^2 values are very low, suggesting a low predictive value in the designated direction.



Contour level = 0.05 MMcf/day, contour increment = 0.05 MMcf/day.

datum .05

Key

etc, 3, 2, 1 } > .05 increasing

A, B, C, etc } < .05 decreasing

Figure 82. Trend surface analysis (4°) using a grid of 417 points of open flow data.

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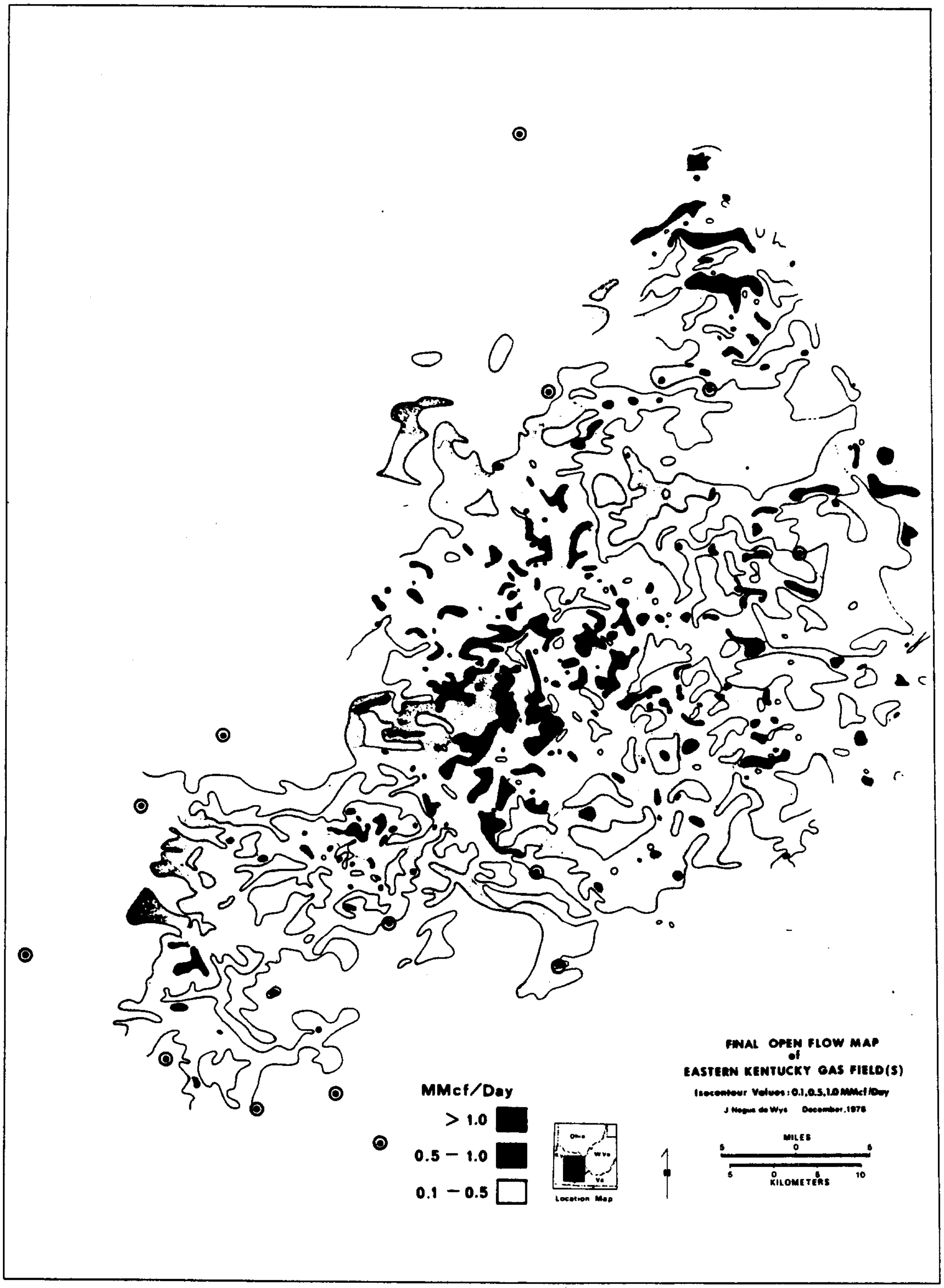
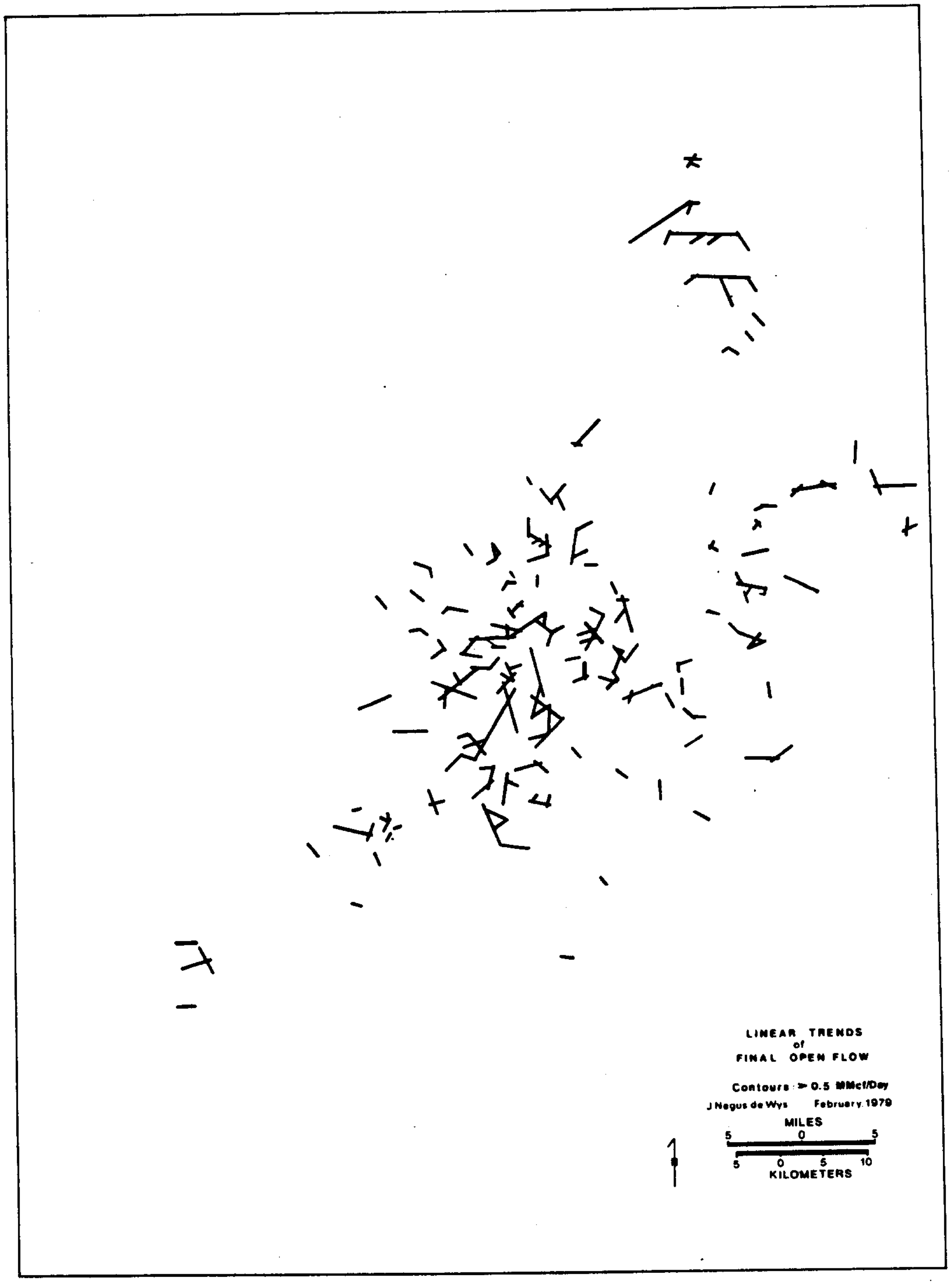


Figure 83. Hand-contoured map of open flow data with three contour levels, using 4750 wells. The highest value areas are shaded to enhance the pattern of higher open flow. Circled dots are locations of wells used in lithology and geochemistry studies.



<u>Figure 84</u>. Trends of high open flow data taken from Figure 83.

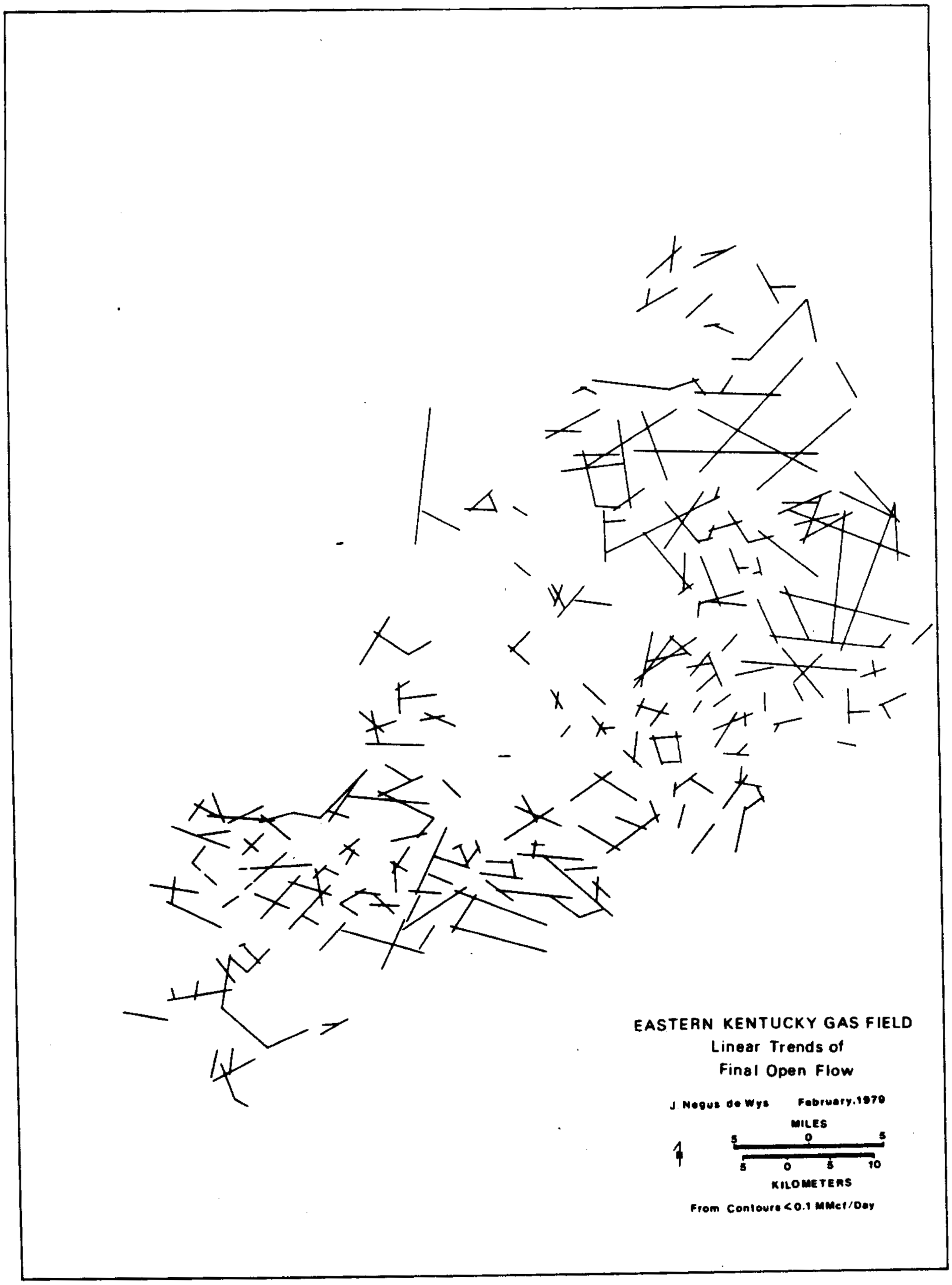
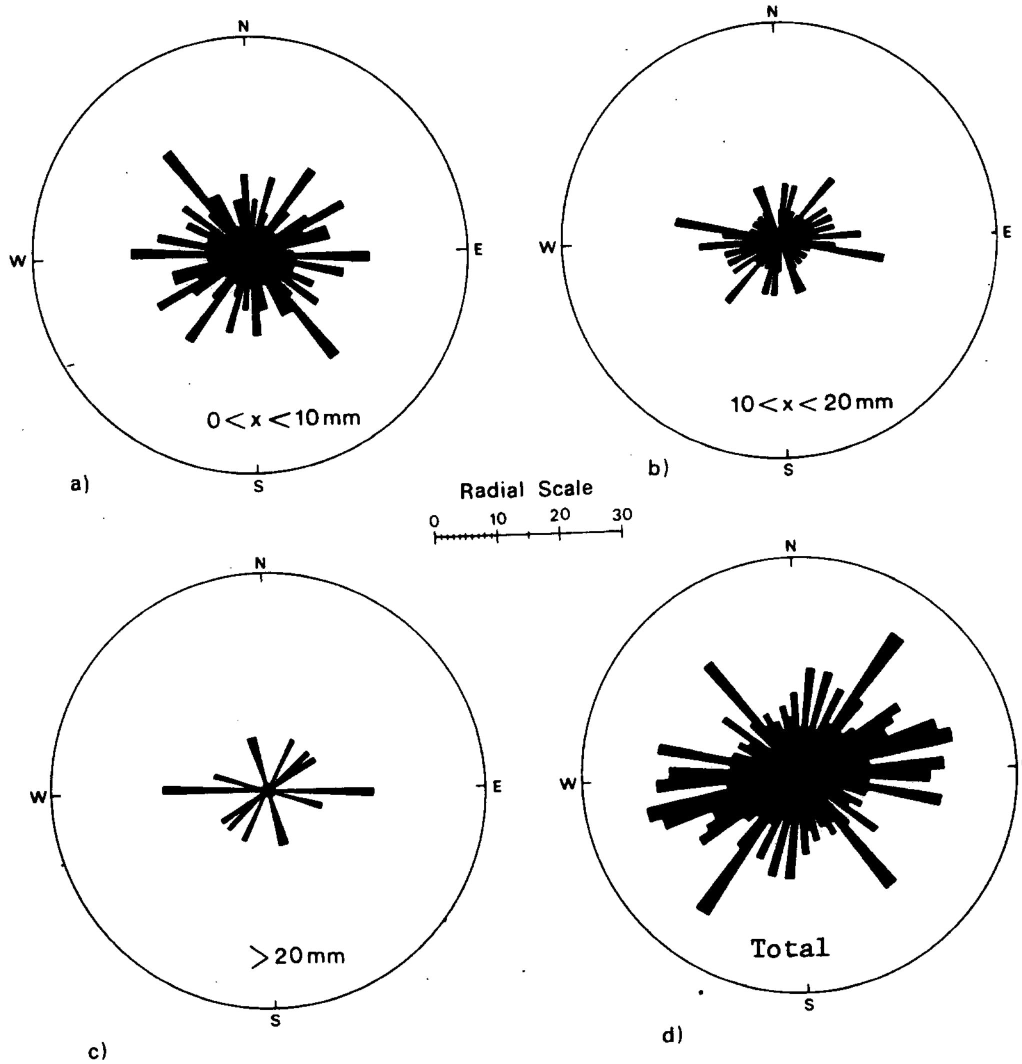


Figure 85. Trends of low open flow data taken from Figure 83.



Polar Plot of High Open Flow Trends

Figure 86. Polar plots of high open flow data trends. The length of trends are measured from a 1:250,000 scale map. Radial scale = number of trends. X = trends.

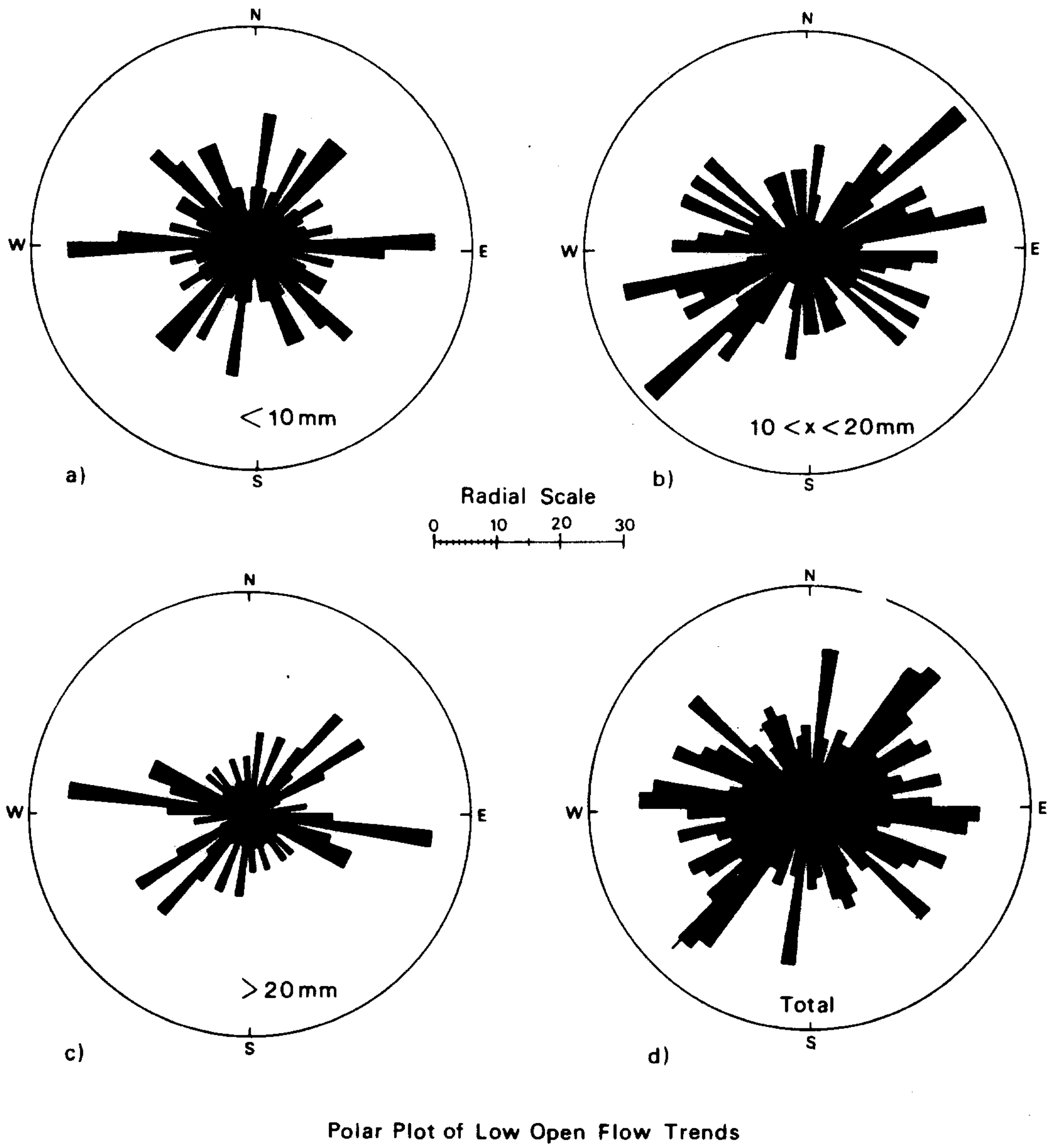
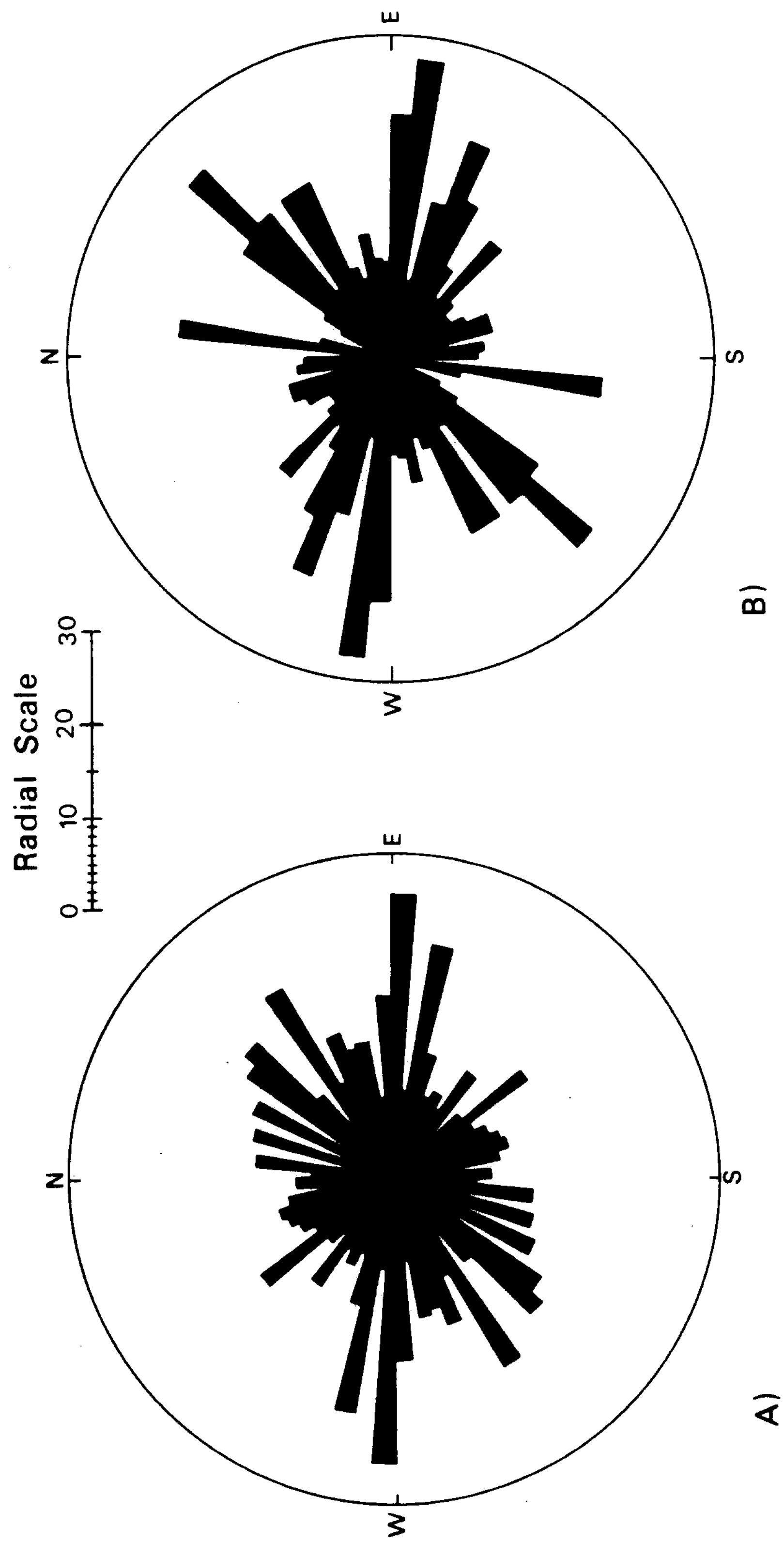


Figure 87. Polar plots of low open flow data trends.
Radial scale = number of trends.
Trends measured on a 1:250,000 scale map.
X = trends.



Polar Plots of A)Cumulative Length of Total High,and B)Total High and Low Open Flow Trends

Figure 88. Cumulative plots of trend lengths of high and low open flow data.
Radial scale = number of trends.
Trends measured on a 1:250,000 scale map.

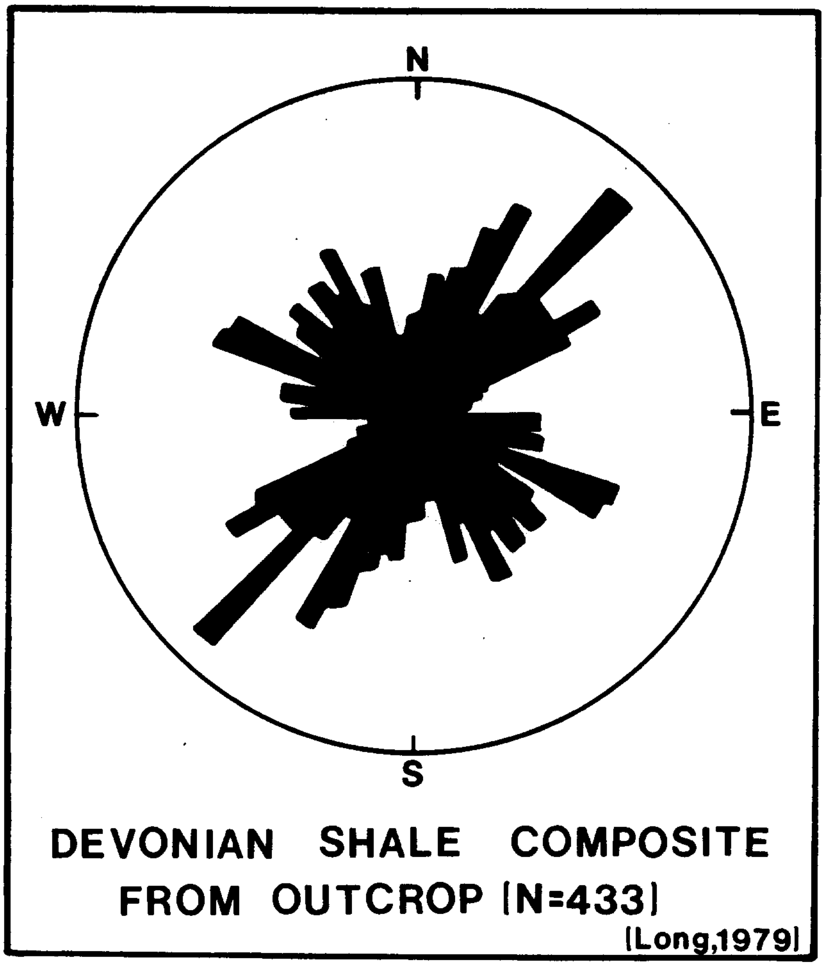


Figure 89. Polar plot of composite of Devonian Shale fracture orientations at outcrop (after Long, 1979).

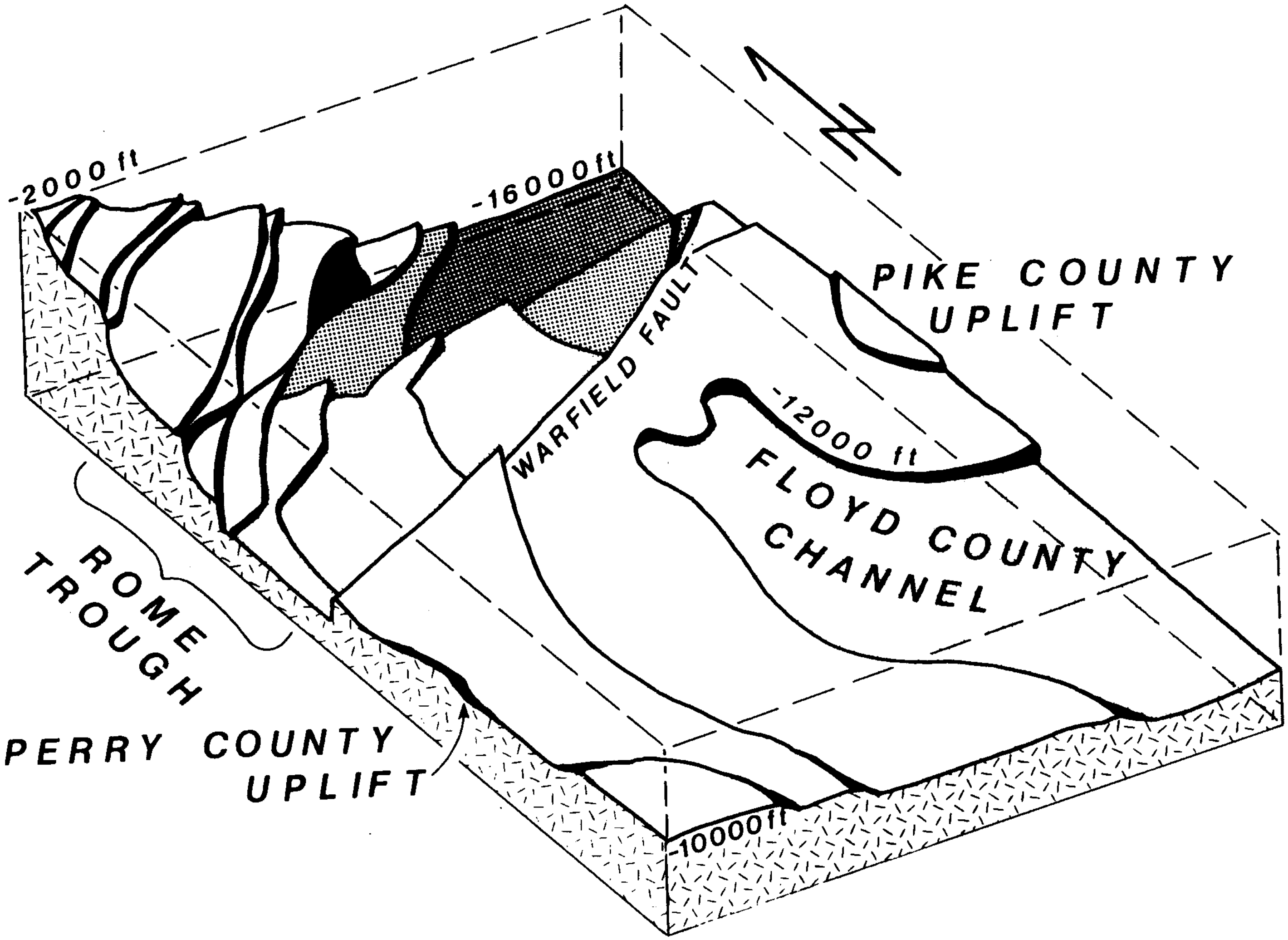


Figure 90. Three dimensional interpretation of basement structure after Shumaker (1977). Breaks are shown on contours. Actual structure would probably be smoothed out between contours except in the Rome Trough area. Note 14,000-foot difference in depth of trough in the northeast corner, when compared with 2,000-foot depth of trough margin.

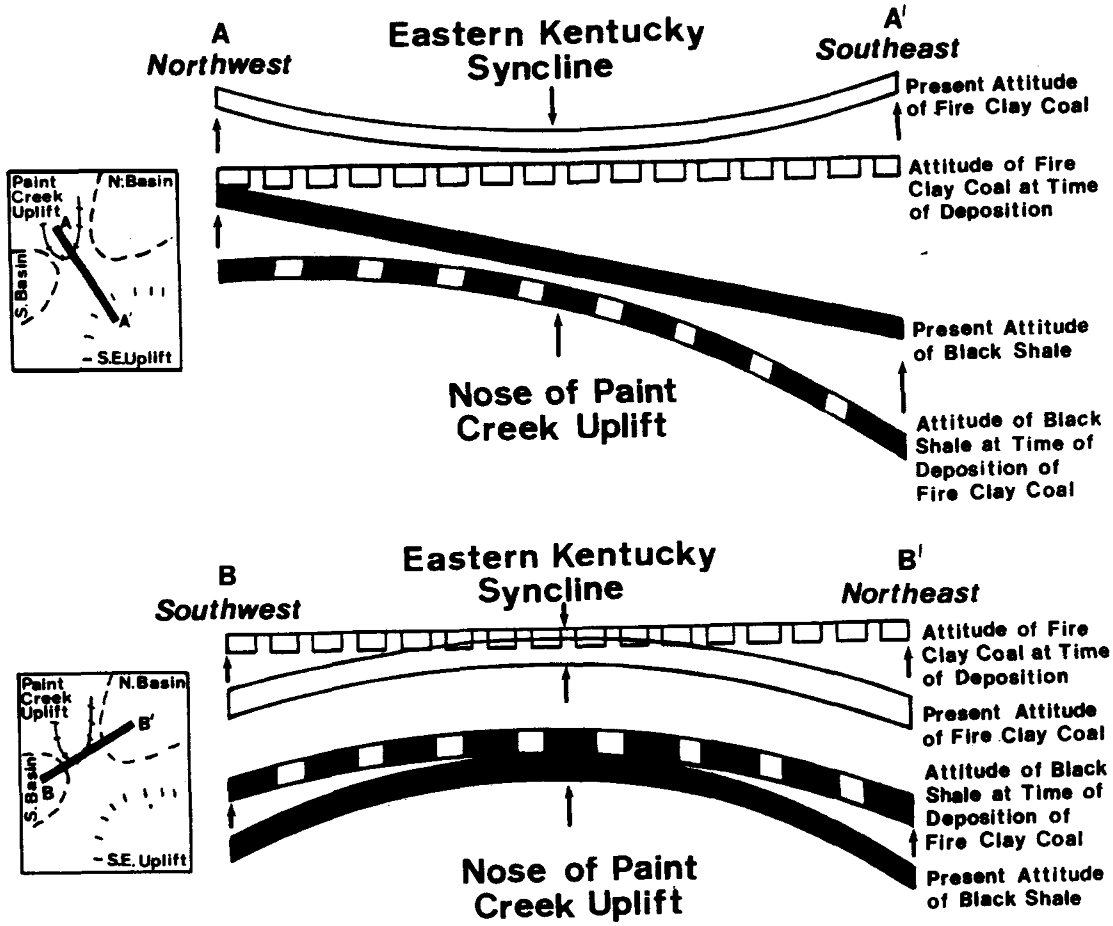


Figure 91. Cartoon comparison of depositional and present attitudes of Fire Clay coal and black shales. No scale is intended. Upper diagram after McFarlan, 1943.

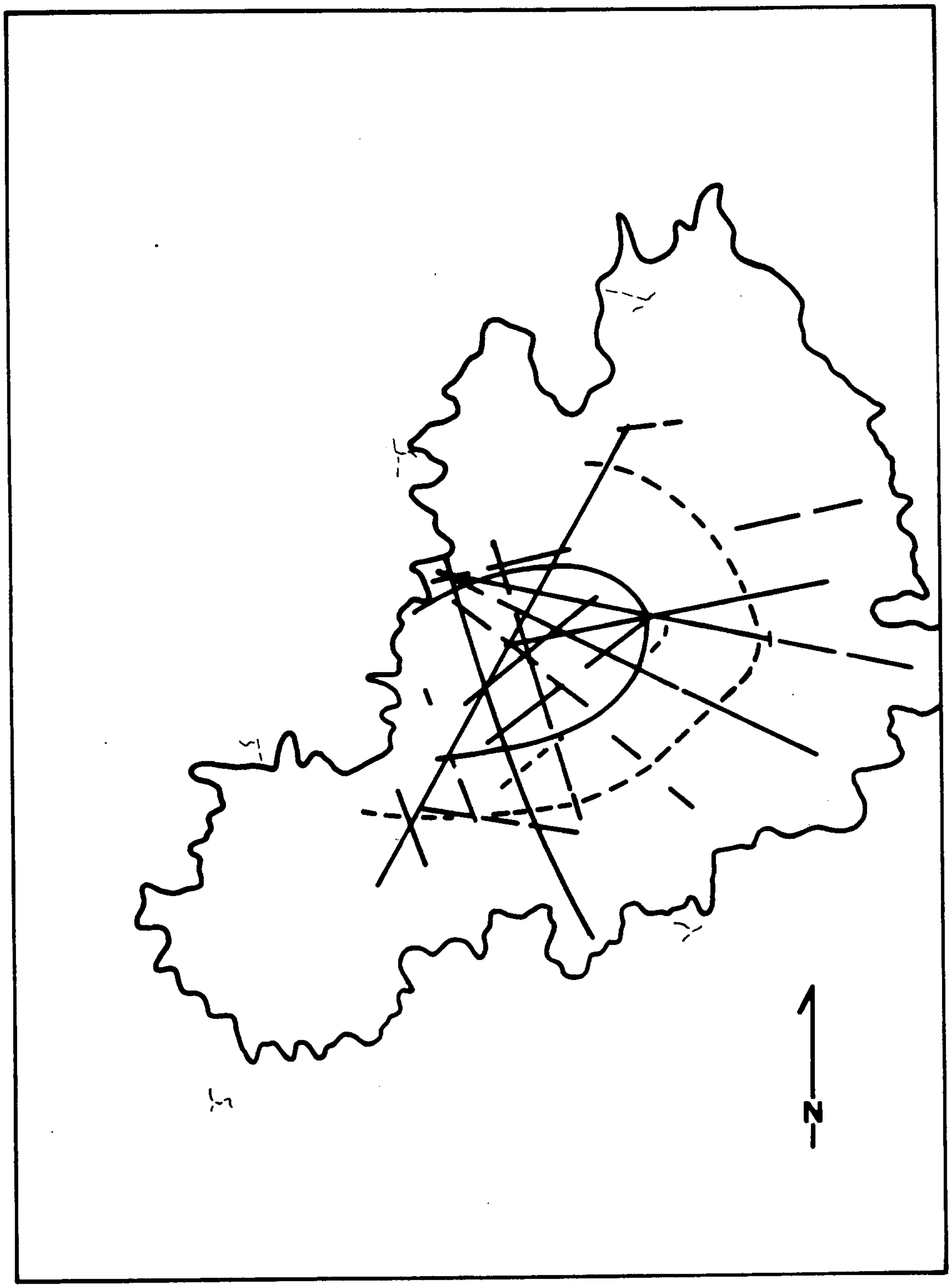


Figure 92. Pattern of open flow basic fracture band trends from Figure 79. Compare with Figures, 73, 74, 80, 81, and 83.

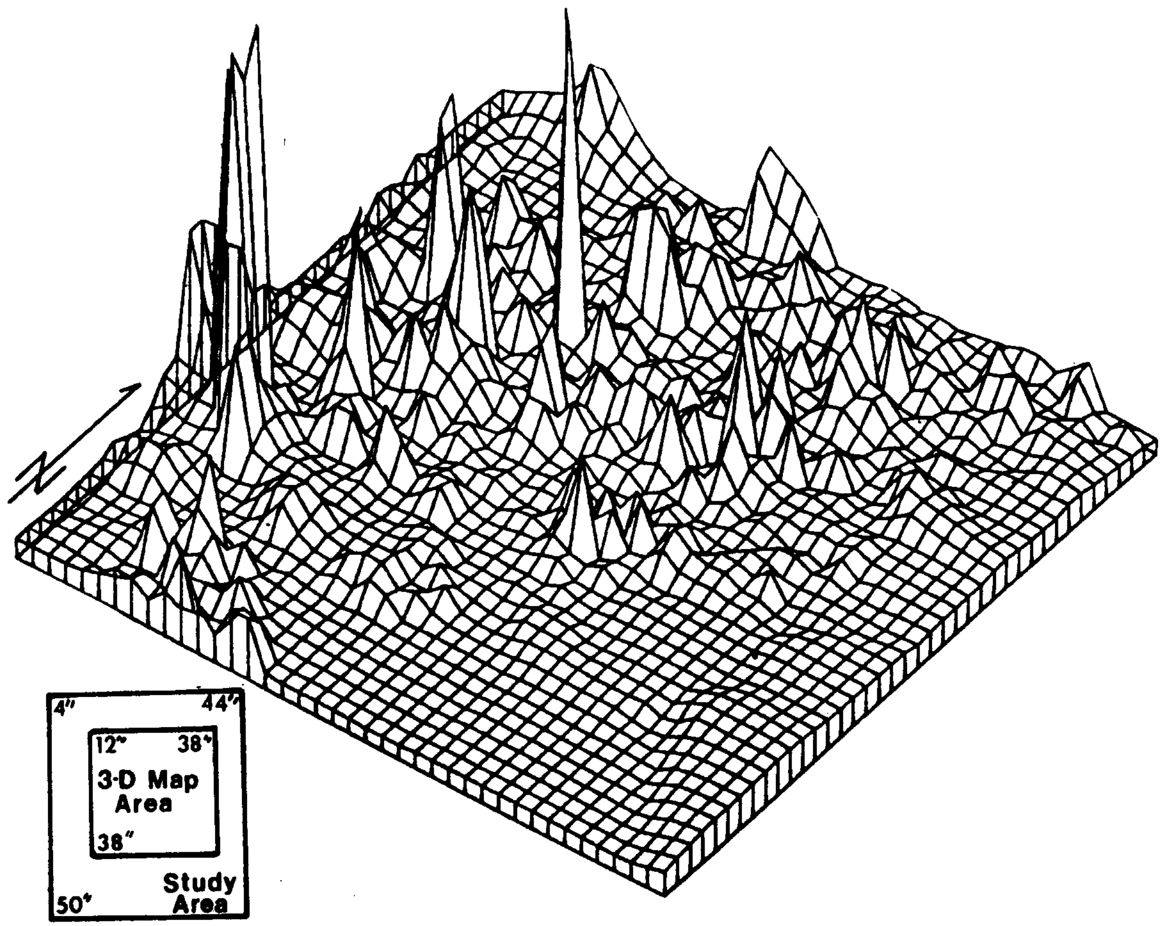


Figure 93. Three dimensional computer plot of open flow data in center of the field. Z-plane is set at 0.25 MMcf/day open flow.

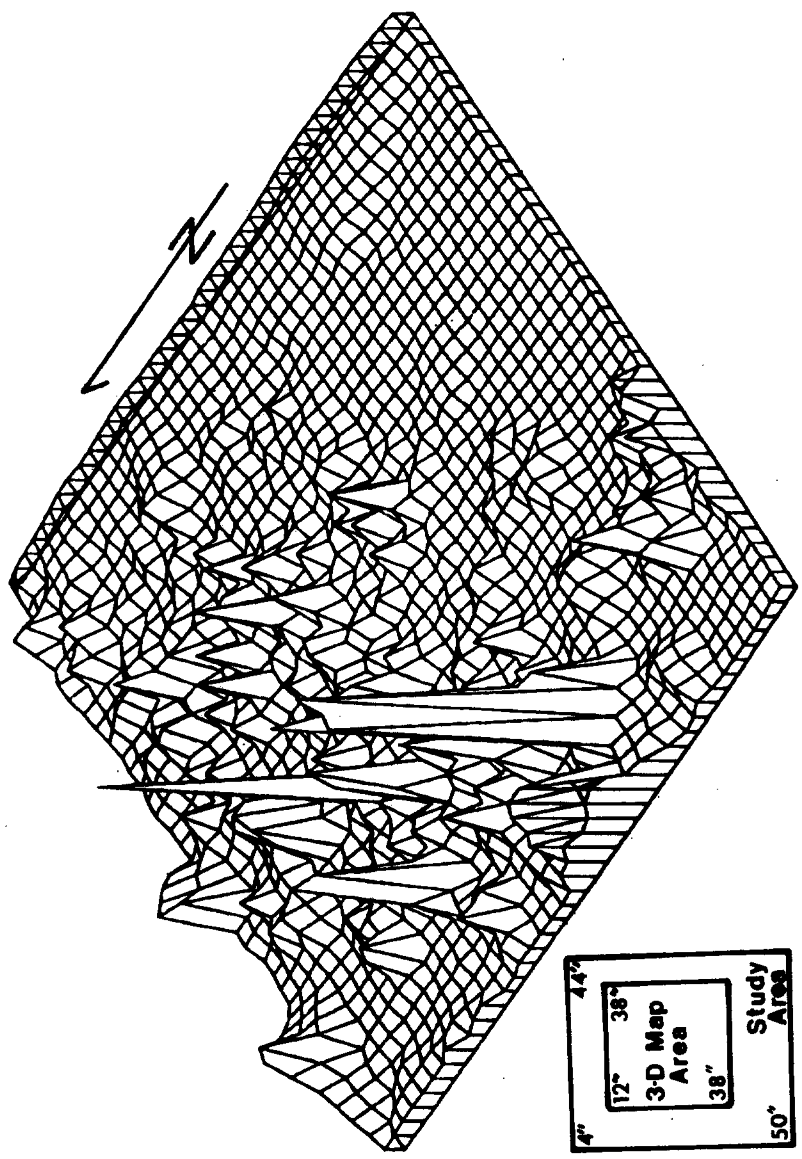


Figure 94. Three dimensional computer plot of open flow data in center of the field with z-axis rotated 90° counter-clockwise from Figure 91.

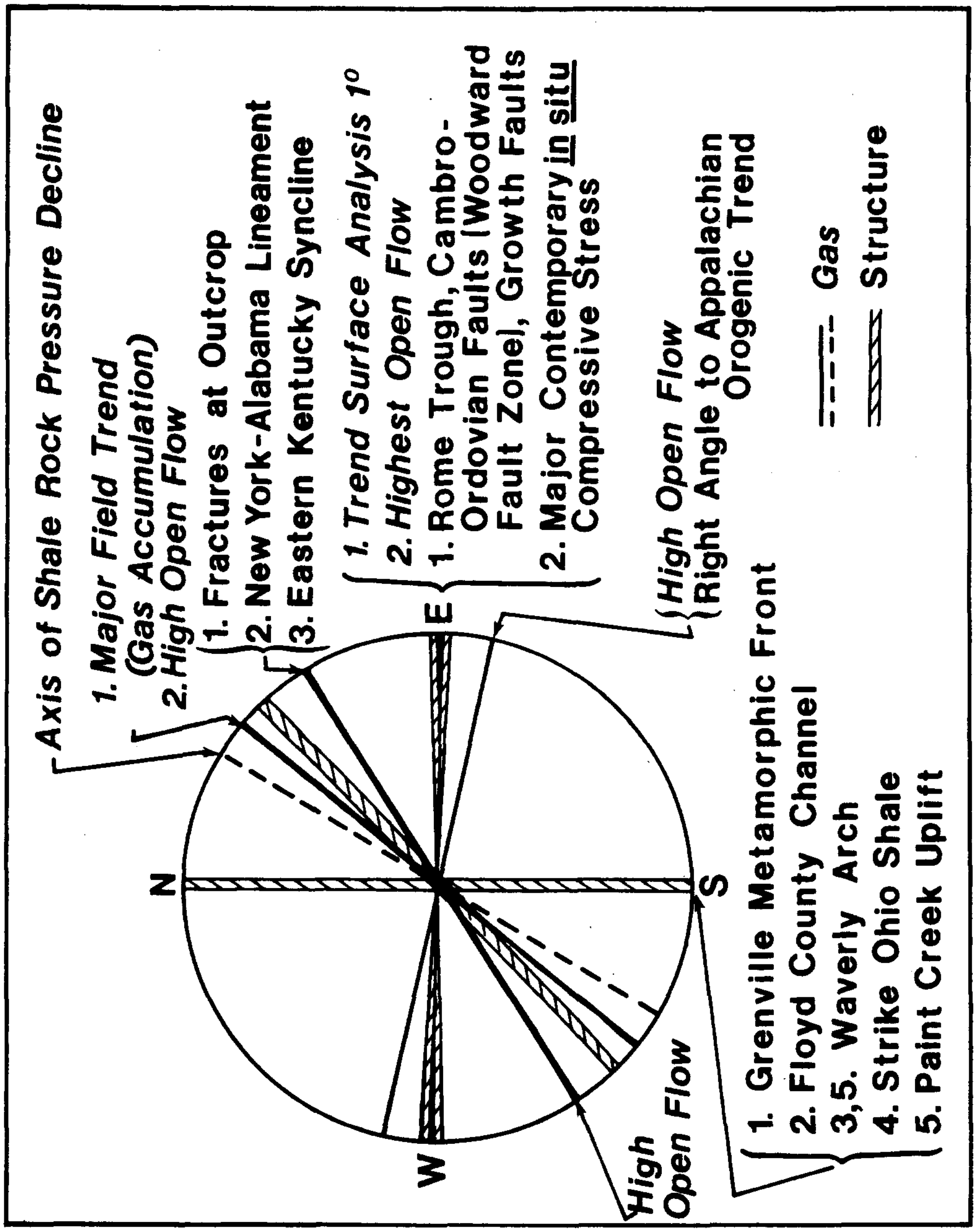
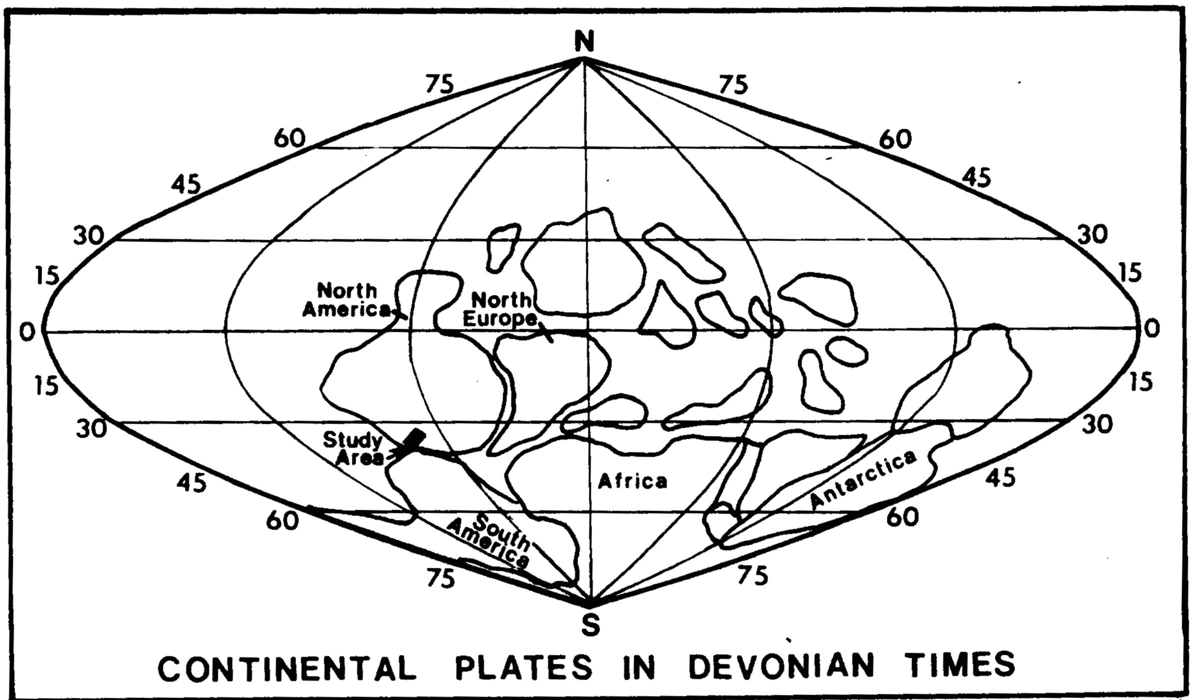
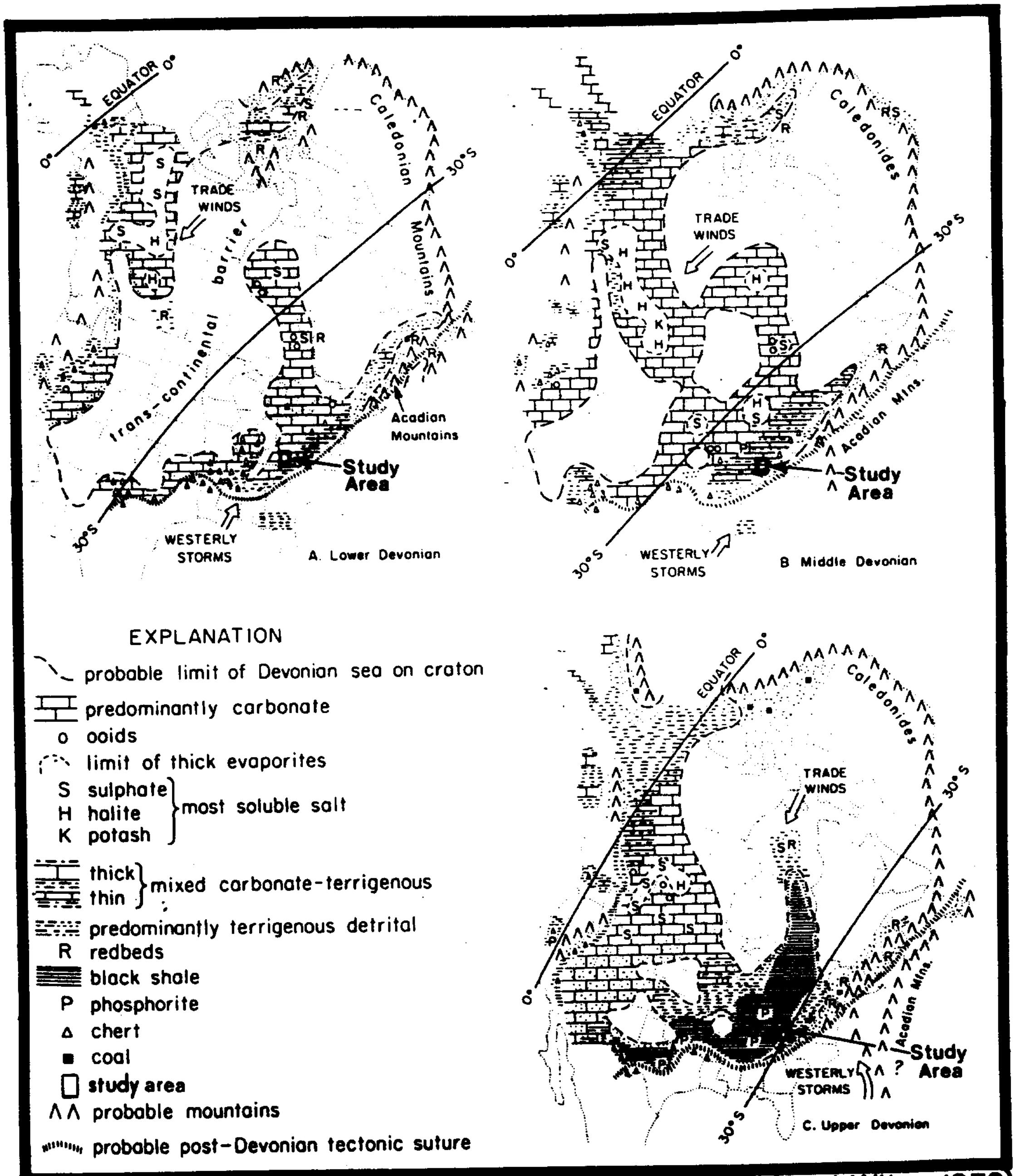


Figure 95. Polar plot comparing open flow trends (italics) with structural trends.



(by permission from Heckel and Witze, 1978)

Figure 96. Position of continental plates in Devonian time (from Heckel and Witze, 1978, with permission). Note position of study area.



(with permission from Heckel and Witze,1978)

Figure 97. Lower, Middle, and Upper Devonian paleogeography (from Heckel and Witze, 1978, with permission).

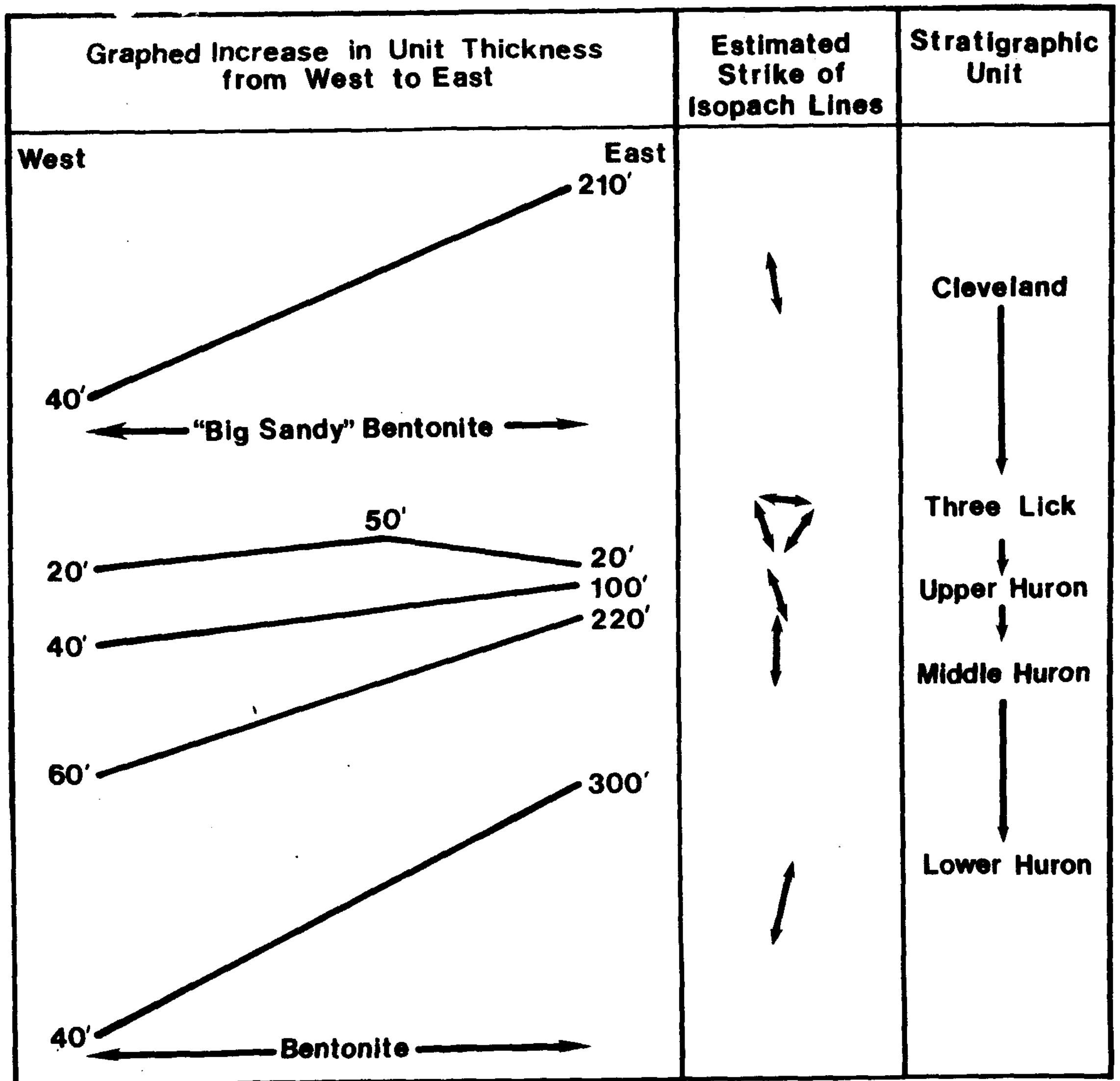


Figure 98. Changes in unit isopach thicknesses across the study area (west to east) related to two bentonite occurrences. Rate of basinal subsidence, interpreted from isopach thicknesses, appears to change with units, and is greatest after the pre-Huron and pre-Cleveland bentonite layers.

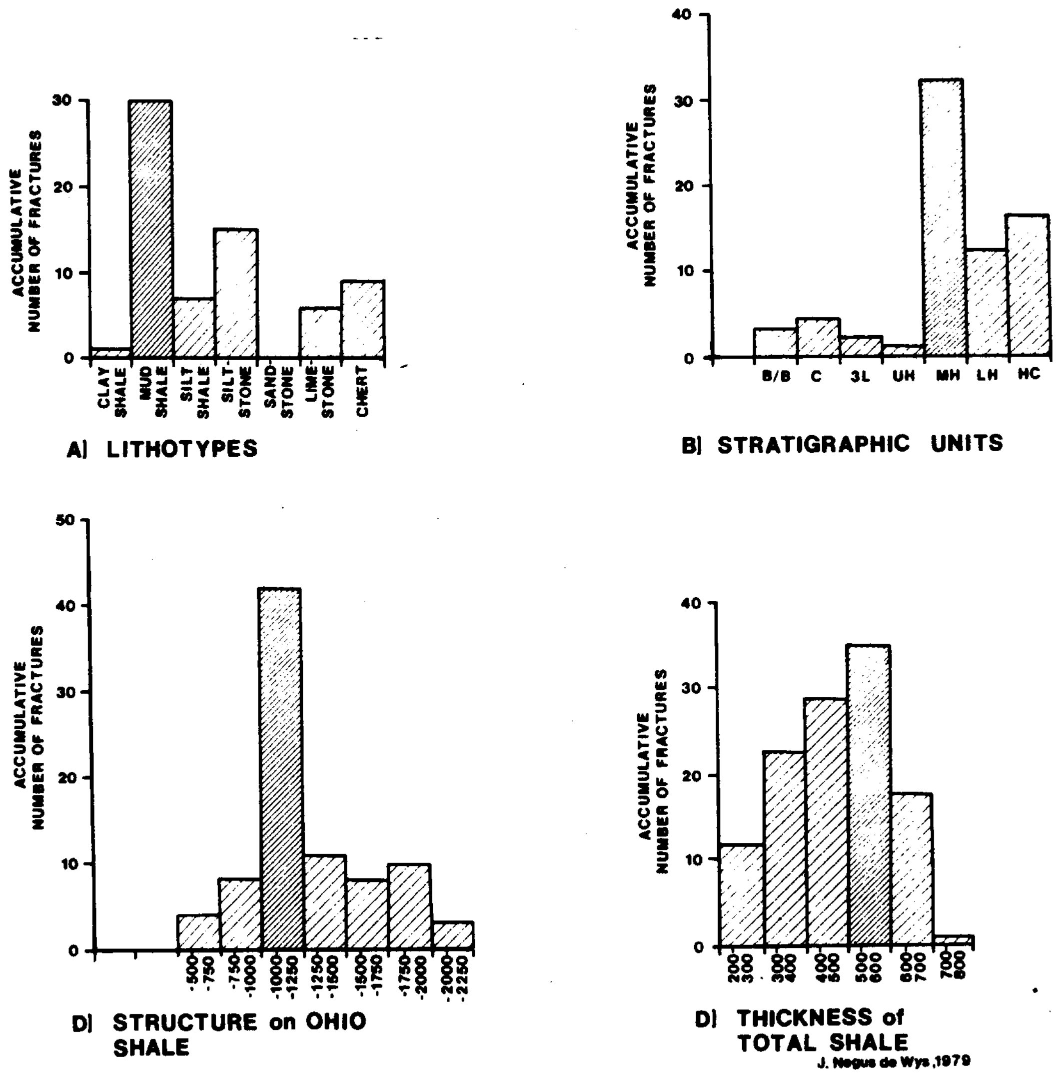


Figure 99. Histograms showing frequency of fractures versus lithotypes, stratigraphic units, structure on top of Ohio Shale, and thickness of total shale. Highest fracture frequency shows greatest correlation with 1) mud-shale, 2) Middle Huron, 3) -1000 to -1250 feet on Ohio Shale structure, and 4) 500-600-foot thickness of total Ohio Shale sequence.

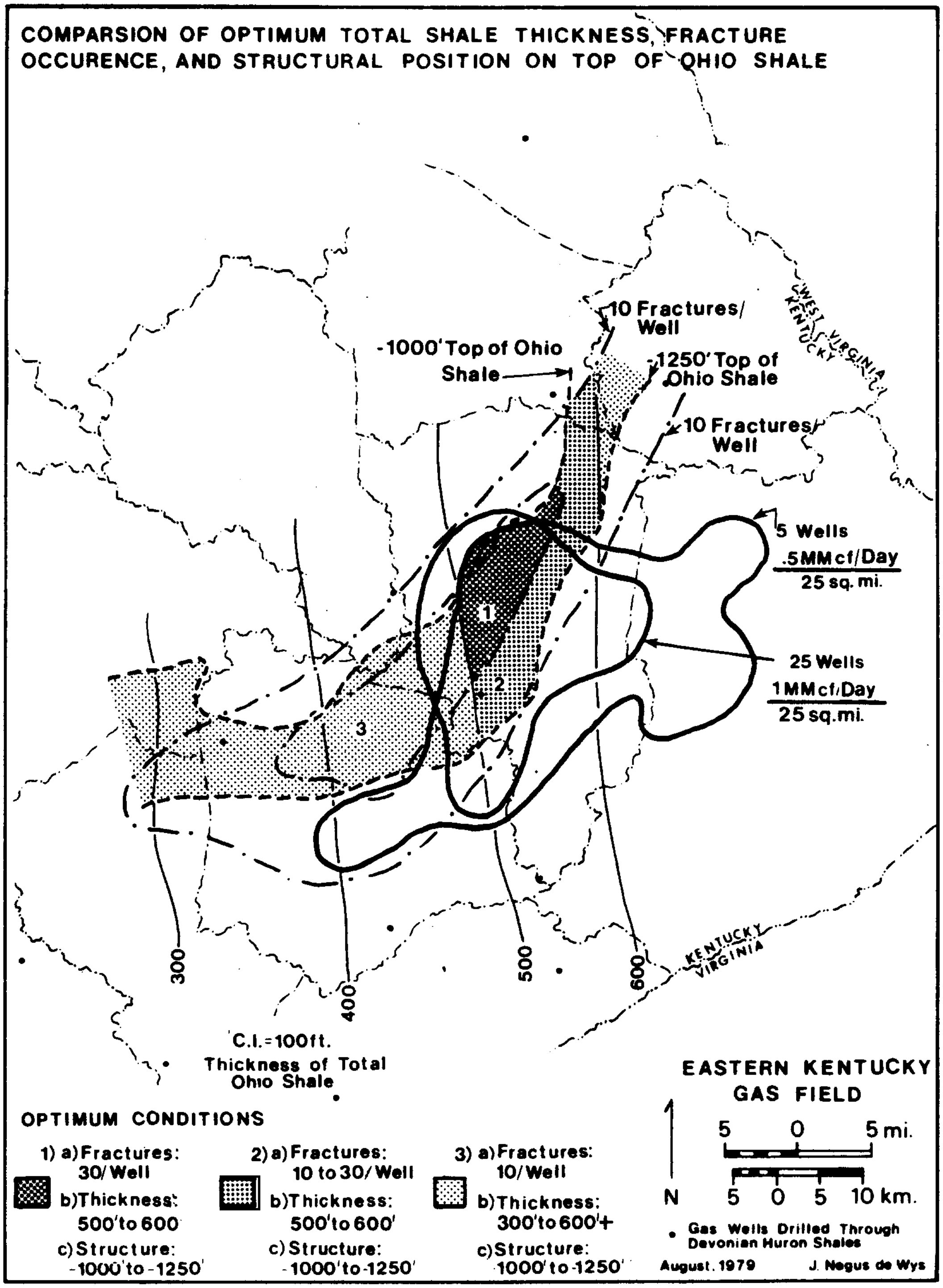


Figure 100. Using fracture relationships shown in Figure 99 priority areas 1, 2, and 3 are presented as predictive of high gas recovery. For comparison, contours of density of high producing wells from Griffith's (1976) two maps are shown.

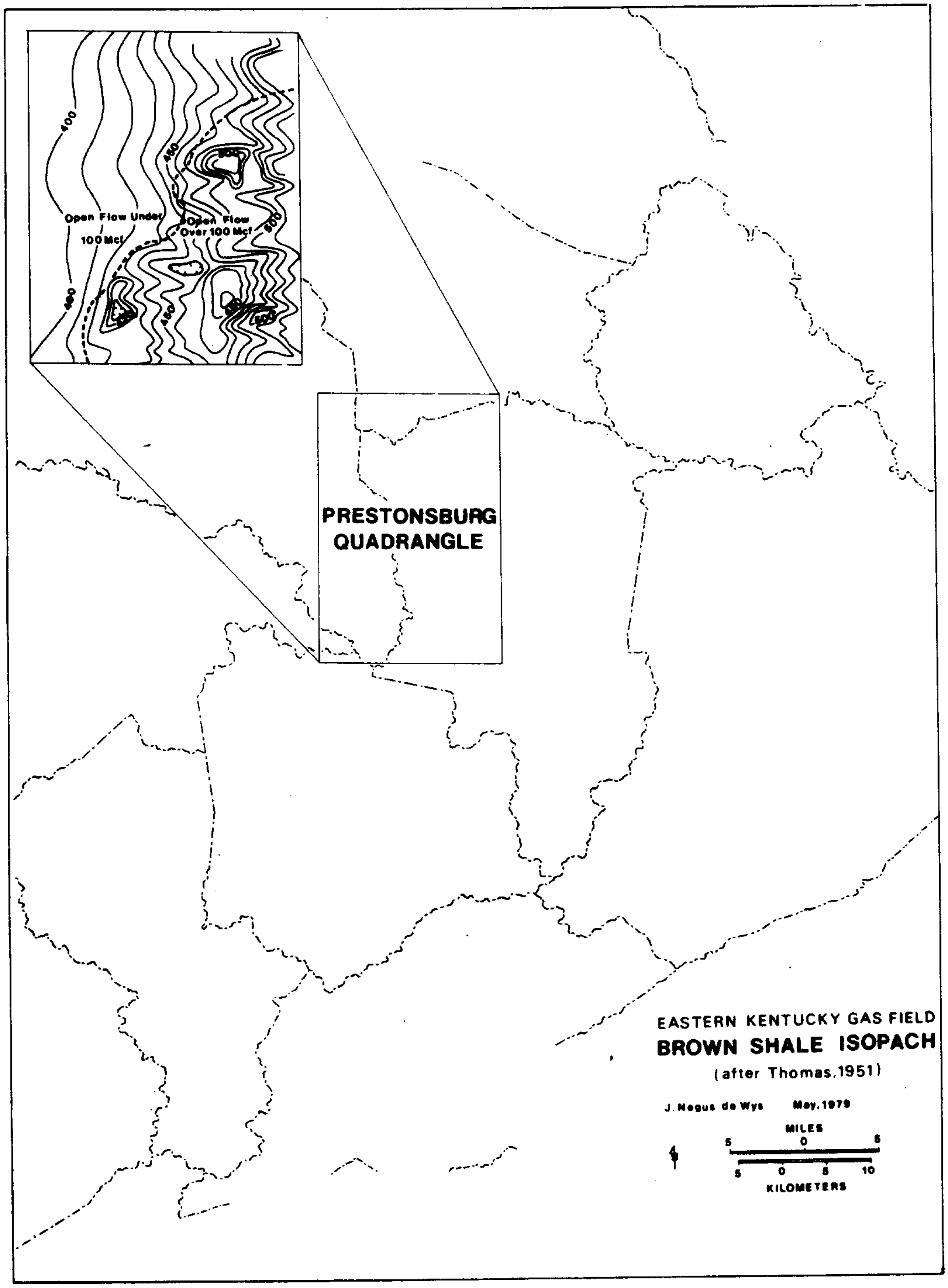


Figure 101. Isopach map of brown shale in Prestonsburg quadrangle, with demarcation line of < 0.1 MMcf/day open flow and >0.1 MMcf/day open flow (after Thomas, 1951).

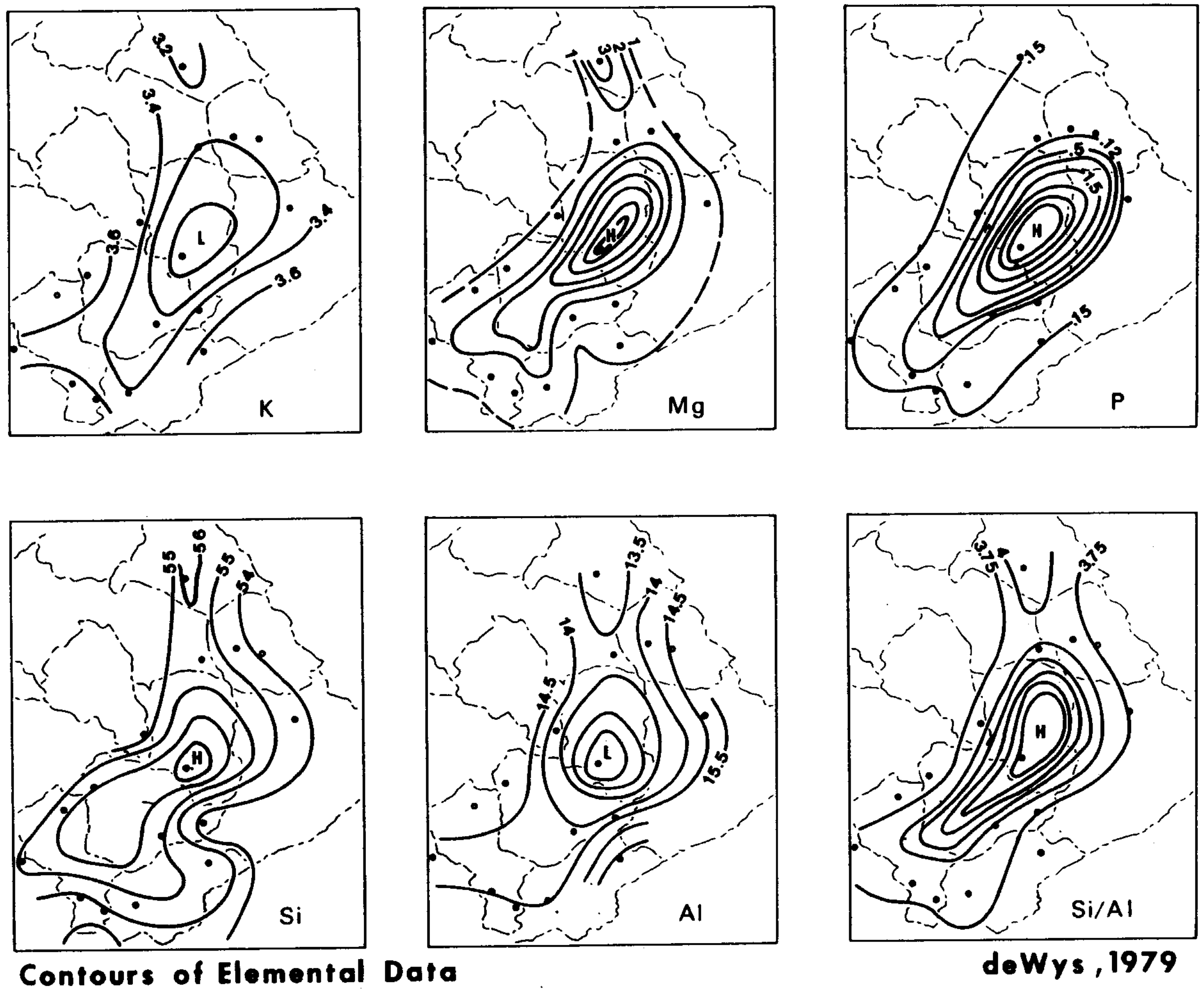


Figure 102. Hand-contoured maps of elemental data representing averages of values for the entire shale sequence. These are some of the maps which showed similarity to the contours of density of high producing wells.

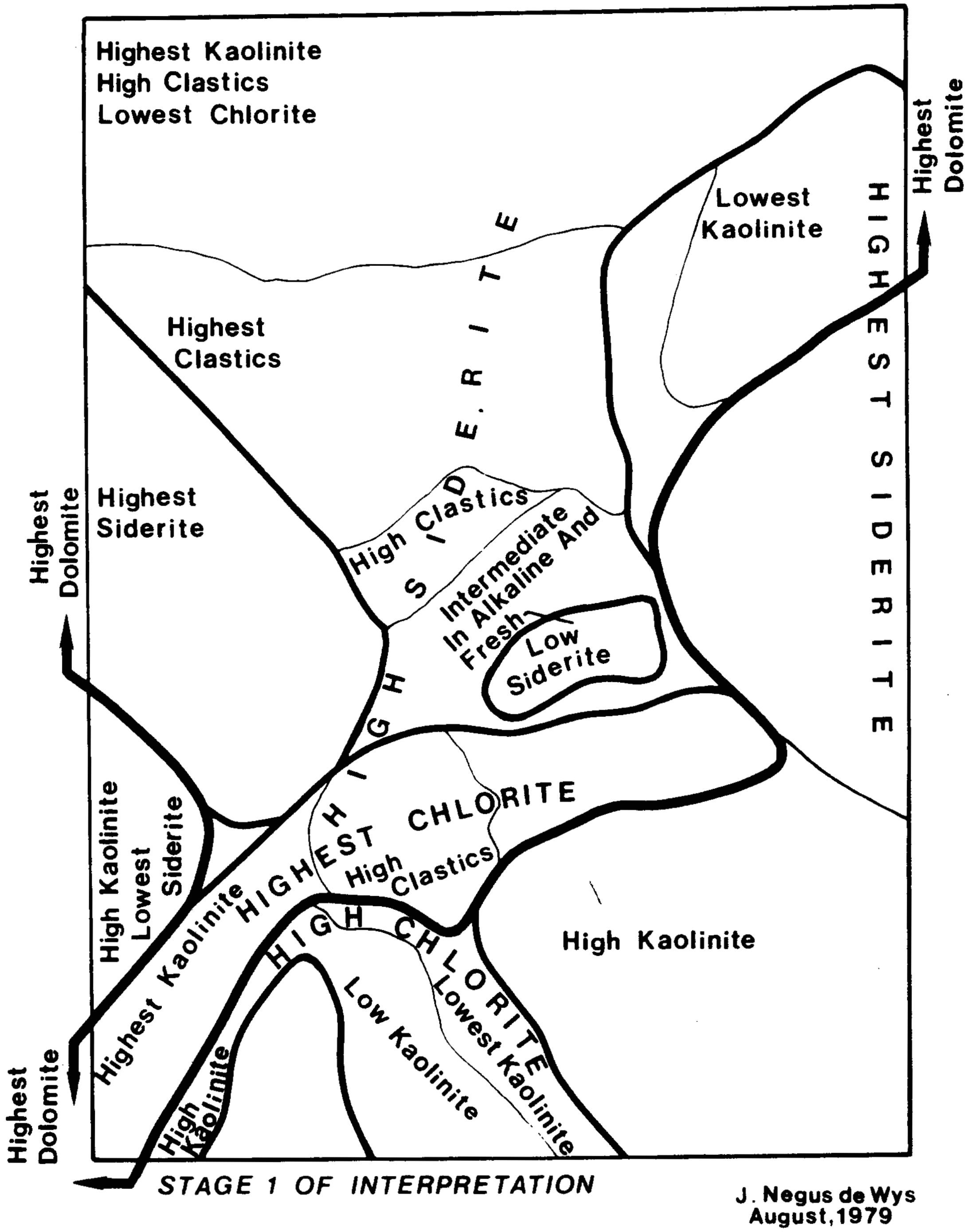


Figure 103. Map showing first stage of geochemical interpretation based on five ratio maps. (Figures 66, 67, 68, 69, and 70).

Jane Negus-de Wys
WVU Dept. of Geology and Geography
Dec. 1979

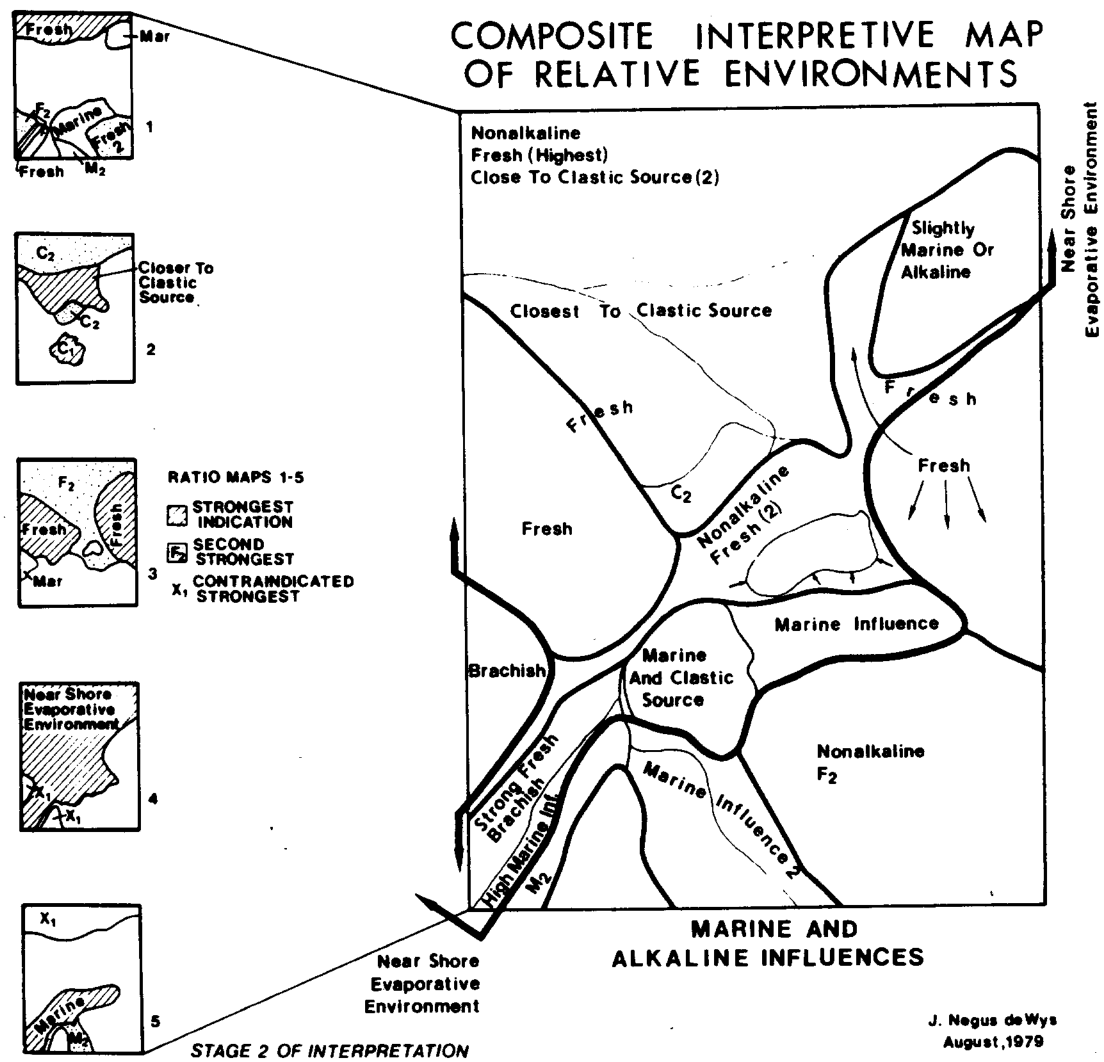
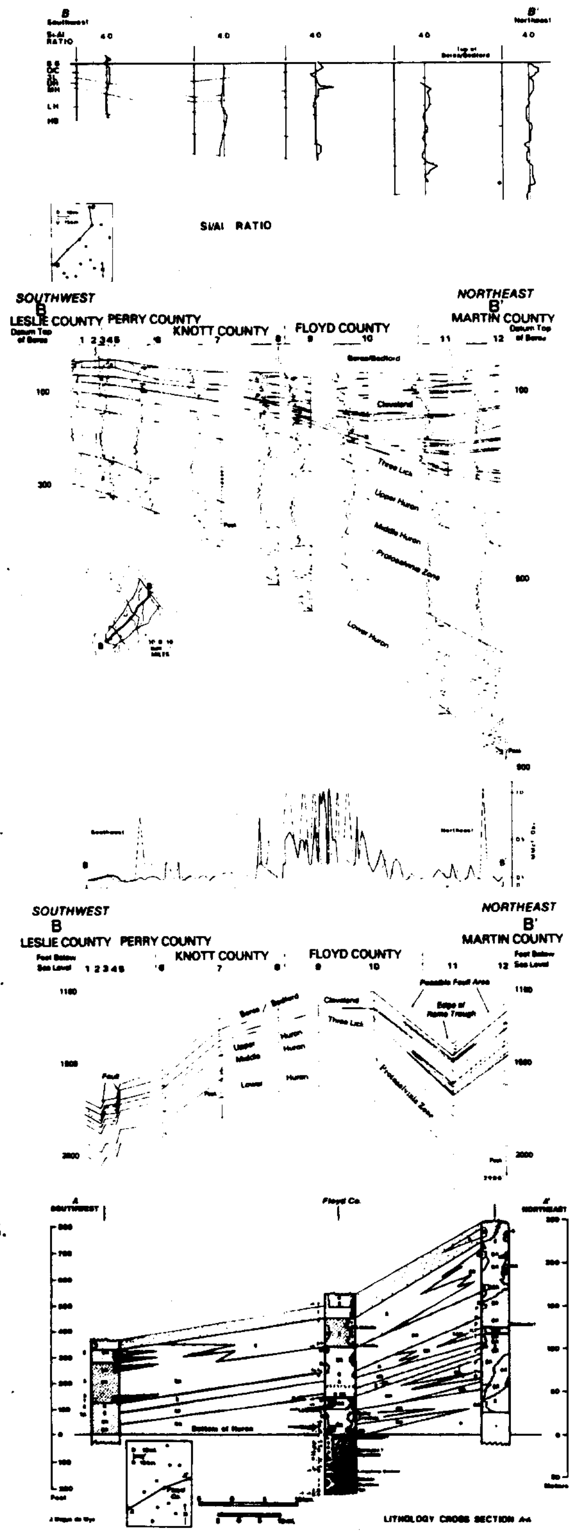


Figure 104. Maps showing second stage of geochemical interpretation based on five ratio maps. See Figure 103.



1. Si/Al ratio for shale sequence. See Figure 60.

2. Natural radioactivity with stratigraphic units. See Figure 18.

3. Comparison of cross section of hand contoured (solid line) with computer contoured cross section (dotted line).

4. Structural-stratigraphic section. See Figure 24.

5. Lithology cross section. See Figure 34.

Figure 105. Comparison of similar cross sections. For details see figures noted.

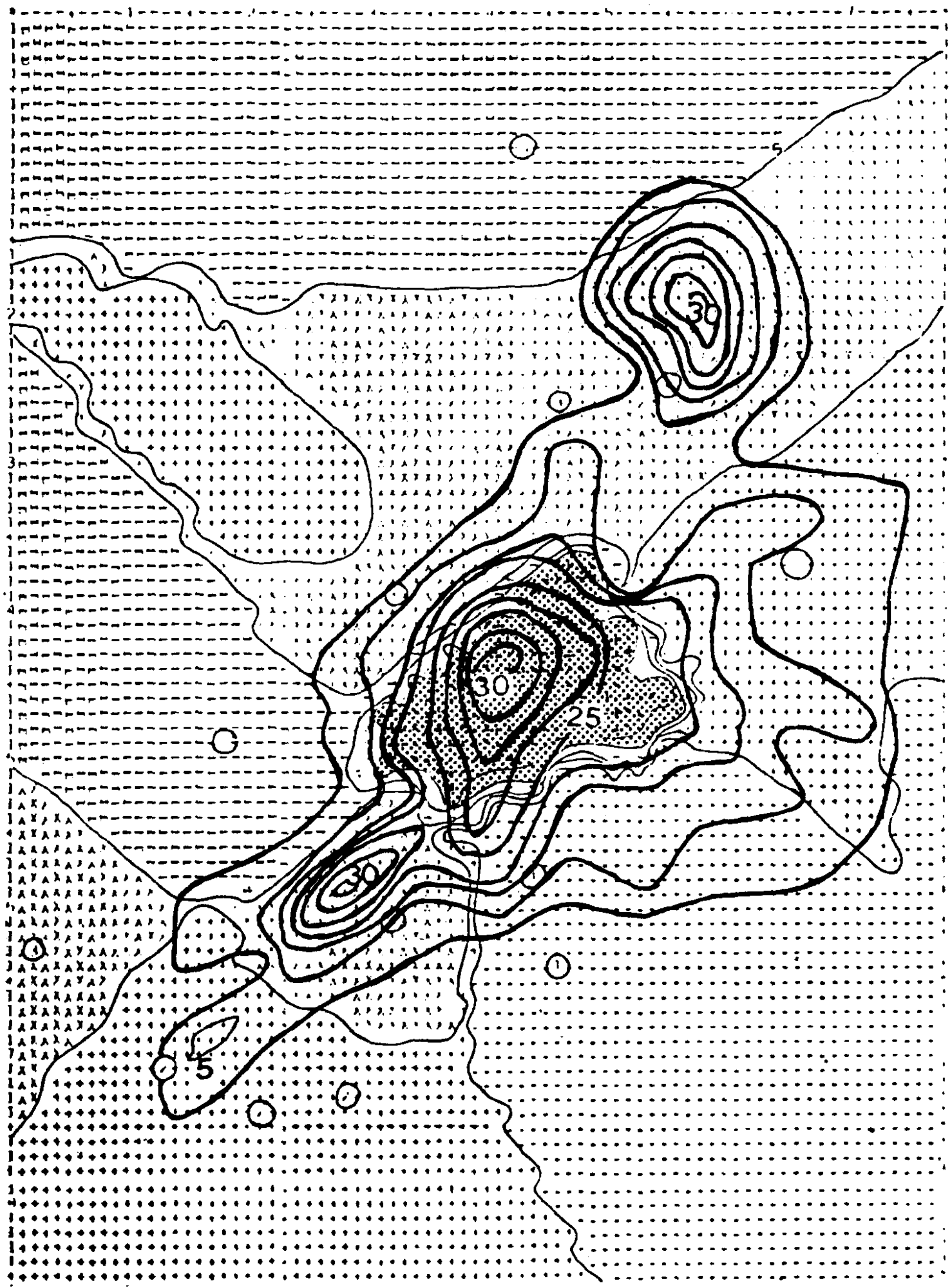


Figure 106. Comparison of Si/Al oxide ratio map (average for total shale sequence) with density of high producing wells 0.5 MMcf/day/25 square miles (the latter map after Griffith, 1976).

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